Exploring Low-Cost Solution for 3D Crime Scene Data Gathering with Immersive Technology

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by

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CERTIFICATION

As the candidate's supervisor, I have approved this thesis for submission.

Supervisor: Dr Omowunmi Isafiade

Signature:

Date:

DECLARATION

I, Mfundo Andrew Maneli, declare that this thesis “Exploring Low-Cost Solution for 3D Crime Scene Data Gathering with Immersive Technology” is my own work, that it has not been submitted before for any degree or assessment at any other university, and that all the sources I have used or quoted have been indicated and acknowledged by means of complete references.

Signed

Date

ABSTRACT

3D crime scene data gathering is critical for law enforcement and investigators during crime scene investigations. Crime scene investigations have seen the effective usage of Light Detection and Ranging (LiDAR) scanners for 3D reconstruction alongside immersive technologies, such as Augmented Reality (AR) and Virtual Reality (VR). However, the inability to afford the existing high-end devices that can offer the desired accuracy of 3D scene data collection in low-resource settings cannot be overlooked, as this may impede crime investigations or render some crime cases insoluble.

In exploring a potentially low-cost mobile solution for 3D LiDAR scannning, this research considered comparing three (3) major factors within the two fundamental AR frameworks, which are ARCore and ARKit, spanning ten different mobile devices with five for each framework. The devices under ARKit are the iPhone 8, iPhone Xr, iPhone 11, iPhone 11 Pro and the iPad Pro 5th Gen. The devices under ARCore are the the Samsung A20, Samsung A32, Samsung S8, Samsung S10 and Samsung S20. The factors explored on these frameworks include (i) AR measurements of items at a hypothetical crime scene, (ii) Plane detection and mapping; and (iii) Resource utilization, such as Central Processing Unit (CPU) and Random Access Memory (RAM). For AR measurements, four measurement criteria were used, ”10cm”, ”45cm”, ”75cm” and ”100cm” at an observer distance of 1 meter and 2 meters with a total of six test runs across all devices. A tape measure was used as a control in the experiment. Findings revealed that ARKit was the more accurate and reliable AR framework between the two frameworks, with an average accuracy score of 97.52% compared to 89.42% for ARCore. For plane detection and mapping, a hypothetical crime scene was explored under two lighting conditions. This was done to gauge the accuracy and light estimation capability of the two AR frameworks. Findings showed that under the first lighting condition (i.e.,40-Watts), ARKit was the preferable AR framework of choice for accuracy compared to ARCore. Under the second lighting condition (i.e, 14-Watts), ARCore was the most preferable AR framework of choice for accuracy under low lighting conditions. For resource utilization, device processing and memory utilization readings were evaluated while the device was idle and once an AR application was running. Findings show that ARKit is the most efficient for CPU utilization. As far as RAM utilization is concerned, ARCore was the most optimized based on the parameters that were tested in the research.

Based on empirical observations from these three aforementioned factors spanning ten mobile devices, the iPad Pro 5th Gen device, equipped with ARKit, appears to be the most promising for crime scene data collection. A structural AR application was then developed using this device to further evaluate three (3) major factors: (i) Quality of 3D scanning based on the utilization of a LiDAR scanner housed in the device; (ii) AR measurements with an extension of the distance criteria, from four to eight; and (iii) 3D scanned scenes localization and re-visitations. For the "Quality of 3D scanning", two hypothetical crime scenes were used in testing. The first in an indoor setting (poor lighting) and the second in an outdoor setting (good lighting). Findings indicate that there are less artifacts in 3D scanning quality when it comes to the outdoor setting compared to the indoor setting. Findings also show that it takes on average 40 seconds longer to scan the indoor scene, compared to the outdoor scene. Regarding the AR measurements with eight distance criteria at 1 meter and 2 meter distances, findings show that for distances ranging from 10cm up to 500cm it is preferable to measure from 2 metres away. For localization re-visitations, the explored low-cost structural AR approach proved that even after a crime scene has been cleared, an investigator can still revisit a crime scene and view augmented data present on the initial scan. The solution presented in this research is critical and could guide future prototyping and application solutions for 3D crime scene data collection, especially in low-resource settings. Furthermore, it is anticipated that this type of exploration and analysis will continue to evolve based on future developments and technology advancement in the field of immersive technology.

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Chapter 1

INTRODUCTION

This chapter presents a general introduction to this study and the motivation for this work. The objectives and goals of this research are also stated. The motivation for this research is the need for accuracy of 3D crime data collection and the issue of productivity faced by investigators in under-resourced environments, which have not been explored in depth by the research community, particularly in Africa. Furthermore, an overview of the research organisation is documented to orient the intended audience about the current research.

1.1 Background Introduction

A crime scene is the location where an offense or activity has been committed and forensic evidence can be collected for further evaluation [1] [3] [4]. It is necessary to register the detailed crime information by precise protocols and using credible measurement techniques. The reconstruction of a crime scene and forensic analysis help in determining the course of events that transpired during a crime [5]. Forensic evidence collection encompasses blood pattern analysis [6] [7], post-mortem 3D full-body documentation [8] [9] and fingerprint analysis [10], to mention a few examples. Figure 1.1 depicts the different research areas that have been explored in this domain of interest and the frequency of paper distribution over the studied years based on a preliminary research that was conducted [1]. Figure 1.1 confirms that 3D crime scene reconstruction is an important aspect of crime scene investigations that has been mostly investigated, as over the studied 17 years, 3D crime scene reconstruction dominated by a staggering 59%.

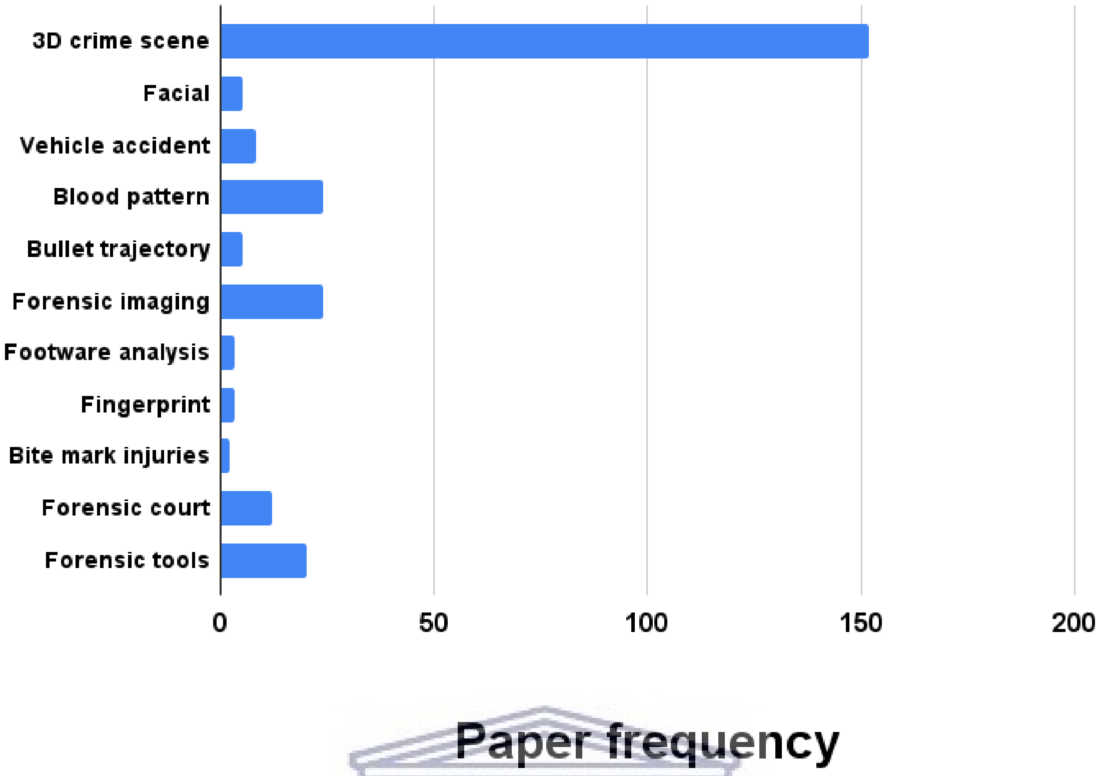


Figure 1.1: Distribution of the sub-focus forensic categories over the studied papers [1].

Accuracy, reliability and integrity are the core fundamentals in ensuring that credible crime scene data has been gathered. Crime scene data needs to be captured at a rapid pace without the risk of contaminating the crime scene [11]. 3D forensic data analysis, capturing and reconstructions are important in ensuring that recorded crime scene data can be depicted in the same manner it was captured in. This information usually aids criminal investigations on jury's decision in court [12], [13].

1.1.1 Crime Scene Data Gathering Context, Its Motivation and Challenges

According to expert knowledge, based on an interview conducted during the research, the nature of information that would usually be collected at a crime scene involves the orientation and positions of items as well as their measurements to determine distance and modus operandi of a crime. Traditional methods of crime scene data gathering encompass: (i) digital media capturing (photography and videography); (ii) hand sketches; (iii) manual measurements and (iv) paper documentations [14, 15, 16, 17]. Based on the studied papers, traditional methods of crime scene data gathering are limited in acquiring accurate and reliable 3D crime scene data [18]. These methods also lack the ability to accurately capture and reconstruct data in 3D [19]. The lack of 3D data capturing poses a subjective single perspective point of view when it comes to analysing a crime scene.

The limitations of the traditional methods have motivated for more sophisticated approaches of data collection and 3D reconstruction. J. Wang *et al.,* [5] looked at the incorporation of the Faro Focus3D S120 model and the High Tech Computer Corporation (HTC) Vive Pro devices for virtual walkthroughs of recreated crime scenes. J. Desai *et al.,* [20] used a terrestrial Light Detection and Ranging (LiDAR) scanner, Trimble TX8b laser scanner and the Faro Focus 3D X330 for accuracy profiling in crash scene reconstruction. S. Zancajo *et al.,* [21] used the Trimble GX and Faro Focus laser scanners for an automatic image-based modelling method applied to forensic infography. Whilst these newly proposed technologies have significantly improved on traditional methods of crime scene data capturing and reconstruction, the cost of these is on the high side, which might pose a challenge in low-resource areas as seen in Tables 1.1 and 1.2 [2].

Table 1.1: Costs associated with PanoScan Point Gun Projected-Light scanner.

Cost category/item	**Low**	**Medium**	**High**
Initial scanner cost			
PanoScan point gun		$11,760	
Initial technology costs			
Data processing computer		$2500	
Tablet computer		$2100	
Point gun software license		$1550	
Annual technology infrastructure			
Server storage costs	$1000		$3000
Training Costs			
Sixteen-hour training (2 trainees)		$1000	
Opportunity cost for trainee Time (2 trainees, 2 days)	$672	$1248	$2144
Lodging for 2 facilitator (2 nights)		$400	

The two tables show that apart from the cost of purchasing these high-end equipment, there are hidden costs associated with training, storage and extra batteries. These could further serve as constraints in under-resourced settings, such as in Africa. Hence, there is a high possibility for delay in crime

Table 1.2: Costs associated with FARO Focus S120 3D LiDAR scanner.

Cost category/item	**Low**	**Medium**	**High**
Initial scanner cost			
FARO Focus S120	$35,000		$60,000
Initial technology costs			
Data processing computer		$2500	
Starter kit		$2100	
Charger and extra battery		$1550	
Tripod		$138	
Annual technology infrastructure			
Server storage costs		$1000	$3000
FARO software license		$160	$2450
Training Costs			
Twenty-one hour training (2 trainees)		$2100	
Opportunity cost for trainee Time (2 trainees, 5 days)	$1680	$3120	$5360
Transportation (Airfare) for two trainees		$900	
Lodging for 2 trainees (5 night)		$1200	

scene data gathering and investigations which may ultimately render some cases insoluble. Moreover, a preliminary investigation with crime scene experts around South Africa confirmed this constraint.

Furthermore, a study conducted on comparing continent-wise geographical distribution of research in the domain of 3D crime scene reconstruction showed that Africa accounted for only 1% of the entire research contribution in the period of 17 years, from 2005 - 2021 [1]. In contrast, Europe and North America combined accounted for 74.2%, which is almost three quarters (75%) as shown in Figure 1.2. This low yield in contribution by the African continent alludes to the fact that Africa is a low-resource continent in comparison to the global outlook [22]. While these newly proposed, high cost and cutting edge technologies exist, the lack of resources in procuring them might prolong or prohibit a crime scene from being solved correctly. Hence, this research explored the possibility of an alternative accurate yielding, yet low-cost solution for low-resource areas within specific parameters.

Several research efforts have emerged [23], [24], [25], [26], which aim to accurately collect and reproduce

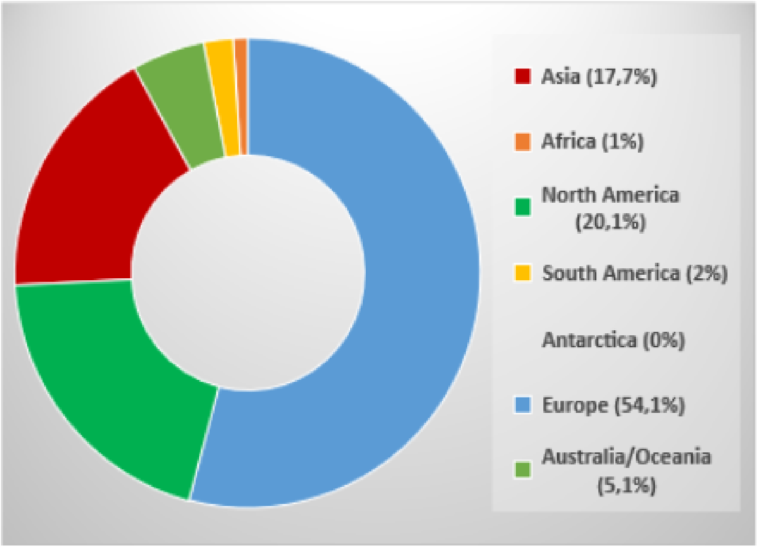


Figure 1.2: Paper distribution across different continents between 2005 - 2021.

3D crime scene data at a low cost. Furthermore, there have been research efforts which investigated the combination of immersive technologies and other technologies such as industrial 3D laser scanners and photogrammetry techniques in crime scene reconstructions [27], [28], [29]. Augmented reality (AR) and virtual reality (VR) are the two primary types of immersive technologies, other forms of immersive technologies exist such as mixed reality (MR) and extended reality (XR), which are both a combination of AR and VR. AR is a technology which can superimpose digital perceptual information in the real world [30], [31]. VR, offers three-dimensional (3D) computer generated immersive environments with multisensory experience for the user. VR relies on 3D stereoscopic head mounted displays (HMD), hand or body tracking and binaural sound [32], [33]. A. P. Gee *et al.*, [34] presented a system aimed at the in-situ 3D annotation of physical objects and environments using AR. The system integrated absolute positioning technology, in the form of GPS and ultra-wideband (UWB) positioning, with real-time computer vision to create a virtual incident map. The VR map was constructed and collaborated by multiple operatives and a remote-control centre. The authors used handheld visual simultaneous localization and mapping (SLAM) sensors tools. They demonstrate in a test environment that covers indoor and outdoor areas and explained how the technology may be used to assist forensic investigators as they collect and process evidence in a crime scene. However, identified issues in the existing methodologies of 3D crime scene data collection and reconstruction encompass cost [2], accuracy [35]and power requirements [36]. Furthermore, crime investigators in low-resource settings need to be empowered in terms of efficient service delivery.

In exploring an alternative solution, this study compared two major AR frameworks, which are ARKit and ARCore. These two AR frameworks were considered based on the two dominating mobile operating systems (OS), Android and iOS [37]. Google provides the ARCore framework and Android OS for an entire range of different smartphone manufactures, while Apple provides the ARKit framework and iOS for its mobile counterparts. These AR framework comparisons were conducted using ten different mobile devices between ARKit and ARCore. The devices under ARKit are the iPhone 8, iPhone Xr, iPhone 11, iPhone 11 Pro and the iPad Pro 5th Gen. Under ARCore, there is the Samsung A20, Samsung A32, Samsung S8, Samsung S10 and Samsung S20. In crime scene data capturing, investigators must capture data with an acceptable level of precision and without the risk of contaminating a scene, hence, the need to evaluate the accuracy and reliability of AR measurements [11]. The consideration to use mobile devices is due to the fact that they are more cost effective in comparison to more sophisticated high-end tools for AR applications such as plane detection. Hence, this research explored the potential trade-offs (costs) that might be associated with using these alternatives under certain factors and conditions. The three major factors evaluated are:

- AR measurements
- Plane detection and mapping
- Resource utilization with respect to random access memory (RAM) and central processing unit (CPU)

For AR measurements, four measurement criteria were used, which are "10cm", "45cm", "75cm"and "100cm" at a distance of 1 meter and 2 meters proximity with six test runs across all devices. A tape measure was used as a control in the experiment. Findings revealed that ARKit was the most accurate and reliable AR framework amongst the two frameworks, scoring an average accuracy of 97.52% as opposed to 89.42% attained by ARCore. For the resource utilization, device processing and memory utilization readings were evaluated while the device was idle and once an AR application was running. Findings show that ARKit on average was the most efficient regarding CPU utilization. However, for the RAM utilization, ARCore was the most optimized. For the plane detection and mapping, a hypothetical crime scene was explored under two different lighting conditions, to gauge the accuracy and light estimation capability of the two AR frameworks. Findings showed that under the first, (i) lighting condition, 40-Watts, ARKit was the preferable AR framework of choice for accuracy compared to ARCore. Under the second, (ii) lighting condition two, 14-Watts, ARCore was the most preferable AR framework of choice for accuracy under low lighting conditions.

Based on empirical observations of these three major factors spanning ten mobile devices, the iPad Pro 5th Gen device, using ARKit, was the most promising for crime scene data collection. This has motivated for further exploration with this mobile device. The accuracy and reliability of the ARKit framework and the iPad Pro 5th Gen gave the best configurations for dynamic ranging and depth perception in crime scene data collection. For the data collection, Vuforia® Engine 10.10 was used to collect and store crime scene data, Unity® Game Engine version 2022.1.22 was used for the mobile AR application development geared for crime scene data gathering. The developed mobile AR application could potentially alleviate the cost barriers that come with the use of industrial LiDAR scanners for crime scene data gathering and help to supplement existing methods of crime scene data gathering.

1.2 Research Rationale, Objective and Question

1.2.1 Research Rationale

The motivation for this research is to explore the possibility of a potentially low-cost solution by means of a mobile AR application that can assist crime scene investigators in low-resource environment. The issue low resources areas face is the inaccessibility to high-end costly equipment for solving crime, this poses a constraint by prolonging or even rendering reported crimes as unsolvable. The developed low-cost solution will need to be as accurate and reliable at 3D data collection relative to more expensive solutions. This proposed solution also aims to help supplement traditional methods of crime scene data collection and allow investigators to capture 3D crime scene data without the risk of scene contamination. The exploration of this solution aims to achieve the aforementioned intentions by utilising the Vuforia® Engine, ARKit and a LiDAR scanner for data collection. T. Sieberth *et al.*, [27] indicated that in the courtroom biased observations were made by the jury based on single-perspective images. Hence, the solution proposed in this research will enable investigators to revisit unbiased renders of already scanned crime scenes with the relevant points of interest (POI) from all angles.

1.2.2 Research Question

The primary contributions of this research are to provide answers to three key research questions (RQ). The main question is "How effective is the proposed low-cost solution for 3D crime scene data reconstruction with immersive technology?" To accomplish the objective of this research, the main RQ has been broken down into the following sub-questions:

- RQ 1: What are the traditional methods of crime scene data capturing? How have these methods evolved and been used by investigators to capture and reconstruct crime scene? What are their limitations?
- RQ 2: How can the development of a mobile application with the integration of immersive technology alongside a 3D scanner supplement accuracy issues posed by traditional methods of crime scene data gathering through 3D crime scene reconstructions?
- RQ 3: What level of confidence can be achieved with the developed mobile application, particularly using the two major mobile AR frameworks (i.e., ARKit and ARCore) of immersive technologies?

1.2.3 Research Objective

The following are the objectives of this study:

1. To explore existing methods of crime scene data collection and identify the strengths and potential gaps in these methods.
2. To explore the use of mobile application for crime scene data collection based on 3 major factors, which are: (i) AR measurements, (ii) Plane detection and mapping and (iii) Resource utilization with respect to RAM and CPU.
3. To evaluate the level of confidence that can be expressed on the developed solution with respect to the two core AR frameworks, which are ARKit and ARCore.

1.2.4 Significance and Economic Benefits

This research contributes to the first set of studies to utilise the iPad Pro 5th Gen's LiDAR scanner in 3D crime scene data capturing. The solution explored in this research could help with some of the challenges faced by crime investigators in under-resourced settings for efficient service delivery. Hence, the reason for exploring a mobile application. Furthermore, preliminary research conducted indicated that there is limited research in Africa in terms of 3D crime scene data gathering as shown in Figure 1.2. This solution will aim to potentially support or bridge the gap between 2D lowly efficient traditional methods of crime scene data collection and reconstruction with low-cost 3D gathering and reconstruction techniques.

Tables 1.1 and 1.2 substantiate the point on why this research aims to provide a low-cost alternative. The tables present two industrial LiDAR scanners with their entire running costs amounting to tens of thousands in United States dollars (USD) whilst the initial cost of obtaining an iPad Pro with a Li-DAR scanner starts at $799 [38]. The developed mobile application could potentially reduce the number of tools used by investigators in court during crime scene revisits. Typical 3D scanners used in crime scenes are exponentially more expensive compared to the equipment used in this study. However, the permissible error margin in the crime domain cannot be overlooked. Hence, the exploration of this solution within different related parameters, such as AR measurements, resource (CPU/RAM) utilization and plane detection were considered.

1.3 Dissertation Outline

This dissertation is organised as follows:

- Chapter one presents a brief background explanation on the importance of 3D crime scene data capturing and elucidates some of the current challenges faced in under-resourced settings in this domain of interest. This section also states the research questions, objectives and discussed what the developed research mobile application focused on. The publications that have emerged from this research are also stated.
- Chapter two presents the related work in this domain of interest, by reviewing research efforts and focusing on traditional methods of crime scene data capturing, types of equipment and technology utilised, the strengths and drawbacks of these techniques. This chapter discussed newer research efforts that have emerged primarily focusing on immersive technologies, types of immersive technologies used and their dominance.
- Chapter three presents the research design and methodology. Firstly, it presents the overall research framework and further elucidate the focus of this research. The design approach, software,

hardware and factors considered in the experimental evaluations of the two core AR frameworks based on the ten mobile devices used are documented. The exploration of the major AR framework factors on ten mobile devices which helps substantiate the reasoning behind the chosen AR framework and mobile device and form a solid foundation for the subsequent low-cost solution exploration was discussed. Furthermore, it detailed the approach to the subsequently proposed low-cost solution for crime scene data gathering. This chapter contains the Data Solution System framework which encompasses the (i) Data acquisition layer, (ii) Processing layer and finally the (iii) Decision support layer.

- Chapter four presents the results and discussion section where empirical observations were evaluated. Results obtained from the research were tabulated and presented in graphical formats for clearer understanding. Tabulated and graphical image data are then discussed and a summary is drawn as to how the proposed low-cost solution performed as well as potential tradeoffs thereof.

- Chapter five highlights the key-points of the entire dissertation, summarised how the research questions have been addressed and provides a future outlook on areas in which this research can expand on and finally concludes the entire research.

1.4 Declaration of Recent Publications

The following publications have emerged from this research:

1.4.1 Refereed Journal Publications

- M. A. Maneli and O. E. Isafiade (2022), "3D Forensic Crime Scene Reconstruction Involving Immersive Technology: A Systematic Literature Review," in IEEE Access, vol. 10, pp. 88821-88857, doi: 10.1109/ACCESS.2022.3199437.

- M. A. Maneli and O. E. Isafiade (2023), "A Multifactor Comparative Assessment of Augmented Reality Frameworks in Diverse Computing Settings," in IEEE Access, vol. 11, pp. 12474-12486, doi: 10.1109/ACCESS.2023.3242238.

1.4.2 Refereed Conference Publications

- M. A. Maneli and O. E. Isafiade (2022), "A Comparative Analysis of Augmented Reality Frameworks Aimed at Diverse Computing Applications," ITU Kaleidoscope- Extended reality – How to boost quality of experience and interoperability, Accra, Ghana, pp. 1-8, doi: 10.23919/ITUK 56368.2022.10003046.

- M. A. Maneli and O. E. Isafiade (2023), "A Comparative Evaluation of Augmented Reality Frameworks: A Plane Mapping and Resource Utilisation Perspective," IST-Africa Conference Proceedings, IST-Africa Institute and IIMC, ISBN: 978-1-905824-70-0.

All four (4) publications are solely from this thesis, the research paper titled "3D Forensic Crime Scene Reconstruction Involving Immersive Technology: A Systematic Literature Review" was utilized in chapters 1 and 2, while the conference articles and journal paper titled "A Multifactor Comparative Assessment of Augmented Reality Frameworks in Diverse Computing Settings" were utilized in chapters 3, 4 and 5.

1.5 Chapter Summary

The discussion in this chapter presents a general overview of the study and motivation for this research, namely the need for empowering crime investigators in low-resource settings for efficient service delivery, by exploring a potentially low-cost solution for 3D crime scene data collection. While several technologies have evolved over the years, as well as methods incorporating immersive technology in this domain of interest, crime analysts in under-resourced settings may not have access to these technologies due to the high-cost. Furthermore, there is limited research in Africa regarding 3D crime scene data collection when compared to other parts of the world. Hence, this research focuses on exploring a potentially low-cost mobile AR solution using several mobile devices from the two major giants. ARKit and an iPad's LiDAR scanner. The general outline of the dissertation is also explicitly stated. The comprehensive discussion of the research outline is presented in the succeeding chapters.

Chapter 2

RESEARCH BACKGROUND AND LITERATURE REVIEW

3D crime scene reconstruction is an important topic for crime investigators and forensic experts because it allows for a much more thorough evaluation of events that transpired during a crime. Whilst several methods have been used for crime scene data collection, these methods have their strengths and limitations. Moreover, 3D crime scene investigation and data collection have evolved from traditional methods to more sophisticated approaches, involving immersive technology. This chapter reviews related work in this domain of interest, to gain an understanding of how existing approaches have contributed to this domain, as well as presenting potential areas for further research.

2.1 Overview of Traditional Methods of 2D Crime Scene Data Collection

Traditional methods of 3D crime scene data gathering play a vital role in the law enforcement department, Figure 2.1 shows a sample hand-drawn image with its corresponding 2D computer generated scene and a LiDAR scanned 3D model image.

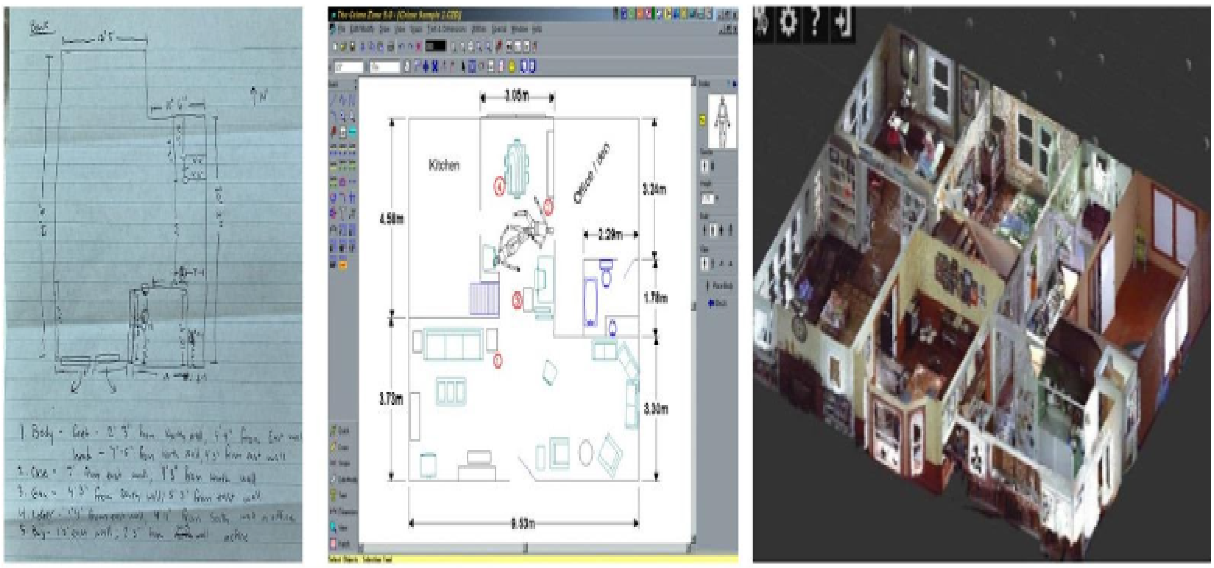


Figure 2.1: An example of a 2D hand-drawn diagram with measurements done by a crime scene investigator (left). Example of 2D computer program for drawing crime scene diagrams and recording evidence locations (middle). The resulting 3D diagram from a 3D scanned scene (right) [2].

Over the years, traditional methods of crime scene data collection have been regarded as inefficient due to their inability to document information in 3D [18], [39]. Traditional methods of data collection need to be precise and hold a level of reliability. Based on reviewed studies, traditional methods of data collection comprise of four categories [1], which are as follows:

1. **Digital media (photography and videography)**
   Videography and photography form the essential backbone in crime scene data collection [40], [41]. The use of digital media allows for investigators to capture and review visual clues of what transpired within a given crime scene [1], [14], [42]. This technique enables investigators to use the captured information as evidence in a jury court [43], [44].

2. **Hand sketches**
   Investigators utilise hand sketches as a mental reminder for what was visually present at the crime scene for example, a layout hand drawing of a room's internal floor plan. Hand sketches can also be used for items currently not visible on scene such as a perpetrator's facial description mentioned by witnesses on scene [1], [11], [45].

3. **Manual measurements**

   Captured digital media and hand sketches need to be accompanied by their respective measurement metric data or else they will be meaningless [46], [15]. Manual measurements are normally captured in a crime scene with either a tape measure, laser finder or a combination of the two [1].

4. **Paper documentation**

   Investigators visiting a crime scene manually jot down points of interest (POI) to mentally remember certain events that transpired which can later be used in court [2], [47], [48]. Investigating officers normally utilize pen and paper to jot down diagrams [1] as shown in Figure 2.1 (left).

2.2 Limitations of Traditional Methods

Traditional methods of crime scene data capturing, and reconstruction have proven to be effective to a certain degree, but several gaps have been identified by researchers. These gaps feature the following shortcomings:

1. **Display limitation:** Computer screens in general visually provide users with information in 2D. These 2D visual displays are used for crime scene reconstructions, interactions with these screens are normally conducted with a computer mouse and keyboard, which work in 2D [19]. These 2D devices lack the Z-axis information, thus only providing a 2D (X and Y axes) viewport. This limited information could lead to subjective court rulings based on the lack of evidence [49].

2. **Low precision:** Investigators visiting a crime scene must identify possible pieces of evidence and then hand-measure their location within a space, using a tape measure or laser rangefinder [2]. Doing so incorrectly can lead to the exclusion of an item of evidence, or extensive argument about its significance or far worse, lead to an inaccurate verdict in court [1], [5], [15].

3. **Image distortion:** Images captured using a digital camera undergo post-processing whereby parameters such as perspective projection, lens distortions and focal length can distort surroundings with respect to their objects or vice versa [15], [50], [51]. These post-processing events can lead to a plethora of issues in crime scene investigations [1].

4. **Restricted time and cost:** Generating 3D reconstructions from 2D sources such as images taken from a crime scene or hand sketches is costly from a financial and processing time perspective

[19], [50]. Hand sketching items in a crime scene is labour intensive and requires a great amount of time to finalise [2], [52].

5. **Potential data manipulation:** It is important for recorded crime scene data to not be erased, altered, or contaminated [11], [53]. Traditional methods of crime scene data capturing are heavily susceptible to data manipulation and corruption. A hand sketched crime scene for instance can easily be altered and any data manipulation could be ruled out as null and void in court as evidence [1], [54].
6. **Human error:** Author D. Raneri [15] states that; "It would be remiss to ignore the human error of a fatigued operator recording their hundredth measurement in the early morning hours, with the potential to confuse the X and Y axes, write down a rangefinder reading incorrectly, or to quite simply overlook an item of evidence". When it comes to a crime scene walk-through, multiple investigators are required to conduct this task due to every single investigator having an individual perspective and even the most diligent and well experienced investigators could make mistakes, especially in complex scenarios [1], [5].

2.3 Related Research on 3D Crime Scene Scene Reconstruction

This section discusses some of the research efforts that have attempted to improve or support traditional crime scene data collection methods. This section also aims to draw contrast on how the proposed methodology fairs against existing methodologies and how it can improve upon these existing methodologies.

2.3.1 Related Research on AR Frameworks

M. Maneli *et al.*, [1] developed and compared two prototype applications for AR measurement accuracy and reliability using ten devices. ARKit and ARCore were the two chosen AR frameworks for comparison. Four distance criteria were used for the comparison across all ten devices spanning ARKit and ARCore. A measuring tape was used as a control, overall finding indicated that on average ARKit had a 99.36% accuracy rating in comparison to ARCore with an 89.42% accuracy. P. Nowacki *et al.* [55] explored the capabilities of ARCore and ARKit platforms for AR/VR applications. The objective of their study was to evaluate the capabilities of ARKit and ARCore and help in choosing the right framework to speed up prototyping and development of modern AR/VR applications. General performance in terms of CPU/memory usage as well as mapping quality were the major criteria examined. Their work however did not describe trends of other AR/VR frameworks, but rather focused on two main technologies, which are ARKit and ARCore. This paper also did not look at the accuracy derived from AR calculations conducted over ARKit and ARCore. Z. Oufqir *et al.*, [56] present a study which implements and concretizes the different functionalities available in augmented reality to enrich the real world with additional information. The objective of their study was to evaluate the capabilities of the two libraries ARKit and ARCore and their capability in the development of augmented reality applications. R. Cervenak *et al.*, [57] in their work, present the possibilities of indoor space mapping and user movement tracking using augmented reality technologies. The objective of their study was to evaluate the possibility of the use of ARKit and ARCore to analyze movement in space without using other navigation technologies. Emphasis is placed on optimizing the algorithms created to track device position in space. J. Borduas *et al.*, [58] present a study which compares the reliability of four mobile 3D scanning technologies and provides insight and recommendations as to which of these are sufficiently reliable for the customization of respiratory face masks. The objective of the study is to compare the reliability of ARCore: Augmented Faces SDK, ARKit: Face Tracking SDK, ScandyPro app using the raw information of the TrueDepth Structured Light sensor and the 3DSizeMe app using the Structure Sensor by Occipital. F. Herpich *et al.*, [59] presents a comparative analysis of augmented reality frameworks aimed at the development of educational applications. The objective of the study is to compare the characteristics of existing frameworks that may allow the development of educational solutions using augmented reality resources, focusing on tools that enable the conception, design and implementation of mobile applications.

2.3.2 Related Research on Plane Detection

J. Rao *et al.*, [60] presents the development of a robust, fast and markerless mobile AR method for registration, geovisualization and interaction in uncontrolled outdoor environments. The developed application was tested within the Wuhan University campus to evaluate the method. The objective of this study was to develop and test on Wuhan University campus. Findings illustrate that the method achieves a high detection accuracy, stable geovisualization and interaction. This paper however only utilised a single obsolete ARCore running device. Overall system utilisation was not checked on a mobile device to gauge the efficiency and optimization. A. Carranza *et al.*, [61] proposed the development of an application that makes use of AR for plane detection. The objective of this application was to label detected objects with tags and relay the information to visually impaired people. This research only presented a basic plane detection Unity build, it never considered the variation of using multiple devices to check for accuracy as done in our research. This research never compared how the different mobile AR frameworks fare when compared to one another. This research never considered or tested as to how optimised the application was or the overall cost to system utilisation. T. Chaudhry *et al.*, [62] presents an overview of ARFoundation and the ARCore SDK library that not only can display but also detect but also insert virtual content in the real world. In this research only one mobile device was used to demonstrate the capabilities of plane detection, light estimation, and efficiency by timing how long it takes to detect a plane. This paper however only used a single mobile device for testing purposes. This paper never considered the ideology of applying more than one AR framework to gauge the disparity between different frameworks. The research paper does not consider plane detection under different lighting settings nor does it verify the CPU and RAM usage once the application is running. P. Nowacki *et al.*, [55] presents the development of a testing application which aims to draw the comparison between ARKit and ARCore for AR and VR applications. The aim of this study was to evaluate which AR framework is the most efficient for prototyping and development in modern AR/VR applications. Overall system utilisation tests were conducted where volatile memory and processing tests were evaluated. This research paper uses obsolete AR frameworks to date. R. Cervenak *et al.*, [57] presents the possibilities of indoor user movement tracking and space mapping using AR. The aim of this study was to evaluate the possibilities of only relying on ARKit and ARCore without the aid of other navigation technologies. This research paper does not compare plane detection times taken under different ambient lighting modes as done in the current research.

Major application domains identified in the studied years include bite mark injuries [63], [64], fingerprint analysis [65], [66], footwear analysis [67], [68], facial reconstruction [69], [70], blood pattern analysis [71], [72], Autopsy [73], [74] and bullet trajectory [75], [76]. Findings in the last decade indicate that prevalent studied papers focused mainly on methodologies that aimed at 3D crime scene reconstruction. Forensic investigation, analysis and data collection could involve several scenarios. 3D crime scene data collection has gained a lot of attention in the past decade, particularly with a focus to complement the traditional methods and or to improve on the shortcomings of these methods. Table 2.1 summarises the research that has been conducted throughout the studied years, with their intended traditional method replacement or enhancement and the types of tools utilized to capture and process crime scene data.

Table 2.1: Summary of proposed methodologies for crime scene data gathering over the studied years (i.e., 2016 to 2021) [1].

		Replaced methods					Tools	
Reference	Research focus	Digital media	Manual measurements	Paper documentation	Hand sketches	Future recommendations	Hardware	Software
G. Galanakis et al., 2021 [77]	3D Digitisation Modalities for Crime Scene Investigation	✓	✓	✓	✓	N/A	Kinect v2 RGB-D sensor FARO Focus LS120 scanner FARO Focus S350 Gom ATOS Compact Scan 5M Go!Scan 50 Leica P40 Z + F Imager 5010X	FARO Zone 3D software Autodesk Recap Unity 3D game engine
L. Luchowski et al., 2021 [78]	Multimodal Imagery in Forensic Incident Scene Documentation	✓	✓	X	✓	N/A	Faro X 130 scanner Z+F 5010C scanner	N/A
R. Jegatheswaran *et al.*, 2021 [79]	Implementation of virtual reality in solving crime scene investigation	✓	X	✓	X	N/A	3-D laser scanner HTC Vive virtual reality headset	Unreal Development Kit
G. Dass *et al.*, 2020 [80]	3D Crime Scene Investigation	✓	✓	X	X	N/A	Multiple cameras Smart phones Computers	3D-Hawk
T. Sieberth et al., 2019 [27]	Applying virtual reality in forensic crime scenes	✓	X	✓	X	N/A	HTC Vive VR-ready gaming laptop Projector Screen Lighthouse Camera	Unity 3D

		Replaced methods					Tools	
Reference	Research focus	Digital media	Manual measurements	Paper documentation	Hand sketches	Future recommendations	Hardware	Software
T. Wieczorek et al., 2019 [81]	Analysis of the Accuracy of Crime Scene Mapping Using 3D Laser Scanners	✓	✓	X	X	N/A	N/A	N/A
P. Ren *et al.*, 2017 [82]	Sketch based modeling and immersive display techniques for indoor crime scene presentation	X	✓	✓	✓	N/A	HandySCAN 700 HTC Vive Desktop	SweetHome 3D Visual Studio Unity3D
N. Zhang *et al.*, 2016 [83]	3D crime scene reconstruction with hand held cameras	✓		X	X	N/A	LiDAR Smart3D Capture	N/A

Table 2.1 presents a summary of how the proposed methods have improved upon and supported crime scene reconstruction over the years. The common denominator amongst these proposed methodologies is that they improve or complement the traditional methods of crime scene data gathering. Each of the four major methods of traditional crime scene data gathering which is improved upon by the corresponding research is marked with a tick symbol ("✓") on Table 2.1. Methods which are marked with an "X" in the table mean that those distinct methodologies did not improve or support the indicated method of traditional crime scene data gathering.

2.4 Research Efforts on Immersive Technologies

While these proposed methodologies have addressed some of the shortcomings of traditional crime scene gathering techniques, it is recognised that there are still existing shortcomings to overcome. These shortcomings have spurred researchers to consider combining the use of already existing 3D capturing methodologies and immersive technologies.

Immersive technologies encompass AR and VR, other forms of immersive technologies exist such as MR and XR which are both a combination of AR and VR. AR is a technology which can superimpose digital perceptual information in the real world [30], [31]. AR can be broken up into the following categories;

1. Marker-based AR; Requires on an image target to function an example of this is a QR code marker [31], [84].

2. Markerless AR; Relies on technologies such as global positioning system (GPS) to provide results an example of this is Google Maps [30], [85].
3. Partially/ Fully superimposed AR; Enables a user to project virtual content partially or fully onto the real world, an example of this would be the Ikea application which allows a user to virtually insert furniture into a real home space [84].
4. Projection-based; Relies on different lighting sources such as lasers to produce a hologram-like outputs an example of this is TeleAdvisor [86].

VR, offers three-dimensional (3D) computer generated immersive environments with multisensory experience for the user. VR relies on 3D stereoscopic head mounted displays (HMD), hand/body tracking and binaural sound [32], [33]. VR can be broken up into the following categories;

1. Non-immersive VR; A user maintains full awareness of the physical environment outside of the virtual world [87] .
2. Semi-immersive VR; More senses such as hearing, sight and smell are immersed compared to non-immersive, but not all [88].
3. Fully immersive VR; Stimulates all of the user's senses [89].

2.4.1 Distribution of Related Research with Immersive Technologies over the Studied Years

Over the studied 17 years the integration of immersive technologies and 3D capturing techniques such as photogrammetry and LiDAR scanning have seen a steady increase as depicted in Figures 2.2 and 2.3 [1].

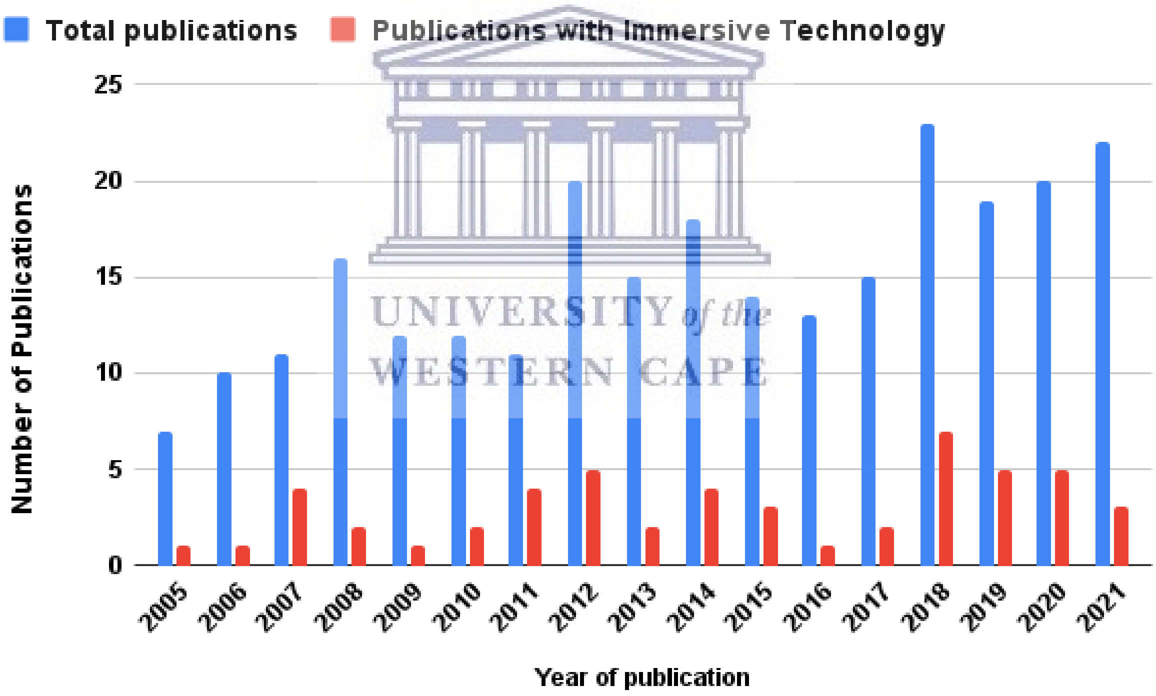


Figure 2.2: Distribution of crime scene reconstruction research with immersive technology trend.

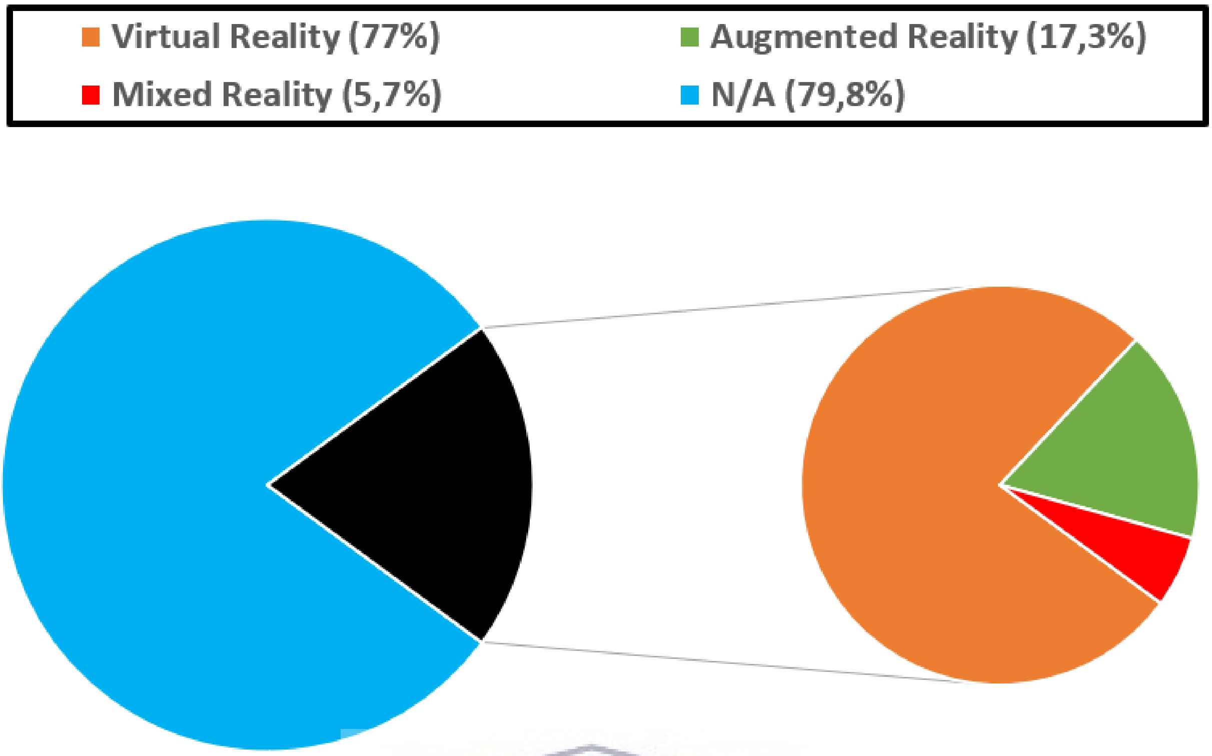


Figure 2.3: Evaluated paper distribution use of immersive technology

2.4.2 Related Research with Immersive Technology

There have been several research efforts that have considered the incorporation of immersive technologies in 3D crime scene data gathering and reconstruction. For example, Sieberth *et al.*, [27] proposed the application of VR in forensics, which allows for a walk-through of the crime scene. This approach improved on paper documentation and image taking. The developed system was formally evaluated by means of it being used in three practical homicide cases. J. Wang *et al.*, [5] presented a portable system that consists of a laser scanner, two hand-held structured light scanners and a VR headset with a mobile power supply to conduct multi-angle and omnidirectional 3D spatial data collection of crime scenes. Findings illustrated that the use of 3D imaging techniques allowed for a more insightful crime scene surveying and several use cases such as accurate measurements, determination of relative blood source locations and clearer injury-inflicting tool comparisons. Table 2.2 depicts a summary of research that utilized immersive technologies for crime scene investigations and reconstructions.

Table 2.2: Summary of proposed research with immersive technologies.

				Mentioned Tools	
Reference	Research Focus	Immersive technology Utilized	Aim	Hardware	Software
T.Sieberth *et al.*, (2019)[19]	A toolbox for the rapid prototyping of crime scene reconstructions in virtual reality	Virtual Reality	Integrating immersive technologies into crime scenes to help visualize captured crime scenes for investigators and the jury.	HTC-Vive, Leap motion, Lighthouses, Desktop PC	SteamVR, Unity (version: 2018.1.8f1) ,3ds Max
J.Wang *et al.*,(2019) [5]	Virtual reality and integrated crime scene scanning for immersive and heterogeneous crime scene reconstruction	Virtual Reality	Providing a realistic virtual crime scene for investigators ranging from 0.6 to 130 meters.	Faro Focus3D S120, HTC VIVE PRO, Lighthouses, Desktop PC	Faro Zone 3D software
D.Raneri, (2018) [15]	Enhancing forensic investigation through the use of modern three-dimensional (3D) imaging technologies for crime scene reconstruction	Virtual Reality	Enhancing imaging technologies through the use of a 3D laser scanner	3D laser scanner, Desktop	3D Modelling software
L.Guangjun, (2015) [18]	A Novel Plan for Crime Scene Reconstruction	Virtual Reality	Providing a VR tour which utilized 360 degree panoramic images taken from a Canon fisheye lense	Camera-Canon 600D, Desktop	3D MAX, Pano2VR

				Mentioned Tools	
Reference	Research Focus	Immersive technology Utilized	Aim	Hardware	Software
U.Buck *et al.*, (2012) [90]	Accident or homicide – Virtual crime scene reconstruction using 3D methods	Virtual Reality	Reduce cost and time taken to train new investigators. Introduce 3D scanners to allow investigators to recreate VR crime scenes	GOM TRITOP ATOS system, 3D laser scanning, Desktop	3ds max

2.4.3 Limitations and Identified Concerns on Immersive Technologies

While the implementation of AR could sometimes be economical, the use cases of AR and VR differ, and they both have their limitations. VR is better suited for visualizing 3D scene environments as the devices can fully immerse the user into the scene. AR, augments the surroundings of a user by superimposing digital elements (images, texts) over a real-world environment. However, the following limitations and concerns of immersive technologies can be noted;

- Motion sickness; A VR headset allows an investigator to navigate around a virtual crime scene whilst physically not moving around in the real world. This causes a synchronous disconnect between the two which could lead to confusion and eventually sickness [91].
- VR headsets are process intensive, usually requiring backup batteries and higher expertise of knowledge to operate [1].
- Dizziness; An output device which houses a low refresh rate, lower than the brain's processing rate may result in dizziness [92].
- Disorientation; Like motion sickness, disorientation occurs due to a user's brain struggling to differentiate between virtual and physical spatial movements [93].
- AR drift; There are various issues to be investigated, which are related to performance, alignment,

and gesture interaction [30].

- Security; There are often no strong security features in this technology [30]. However, the incorporation of artificial intelligence and blockchain technology could assist in this regard.
- The Microsoft HoloLens manual identifies potential side effects such as nausea, motion sickness, dizziness, disorientation, headache, fatigue, eye strain, dry eyes, and seizures [91], [94].

2.5 Chapter Summary

The discussion in this chapter presents a general overview of the background research, namely the literature review containing an in-depth overview of traditional methods of crime scene data gathering, the types of techniques used in crime scene data gathering as well as the identified limitations. The reviewed literature mostly focused on crime scene data gathering revolving around 3D reconstruction, Blood pattern analysis, and Forensic imaging, to mention a few. However, none of these papers focused on the admissibility of crime scene data. This chapter also presents the related research studies, the proposed methodologies which aim to improve upon traditional methods of crime scene data gathering as well as introduces research efforts involving immersive technologies. The exposition in this chapter creates a balance on research efforts in the last 17 years and areas that could be further explored for improvement.

Chapter 3

DESIGN AND METHODOLOGY

This chapter presents the methodology of the study and further elucidates the approach explored for the low-cost solution. The major factors explored in the experiment are detailed, as well as the evaluation metrics used to determine the potential usefulness of the solution and possible trade offs within the context of the parameters that are considered in this research. The development and design processes are described to provide details on what has been taken into consideration when creating the mobile AR application for crime scene investigators. Two hypothesized (indoor and outdoor) crime scene areas are used for the testing and data gathering.

3.1 Design Framework

The overall framework of the proposed solution is presented in Figure 3.1, and how it fits into the context of assisting crime investigators. The framework consists of three major layers, which are (i) Data acquisition layer; (ii) Processing layer; and (iii) Decision support layer.

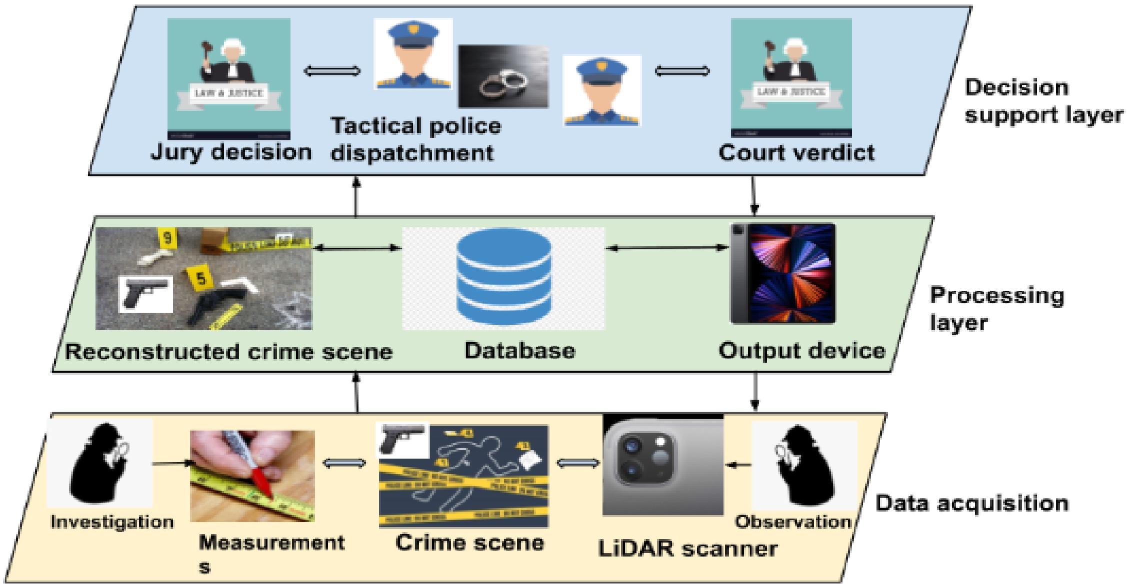


Figure 3.1: Framework of the 3D Crime Scene Data Solution System.

3.1.1 Data Acquisition Layer

The data acquisition layer is where all the crime scene related data such as fingerprints [95], [96], blood spatter [97], [98], [99], [100], full-body documentations [8], [9], [101] to mention a few can be collected. This raw data needs to be captured in order to decipher the modus operandi and suspects of a crime scene. This data is normally captured using digital media (photography and videography), hand sketches, manual measurements, or paper documentation. Data collected in this layer needs to be accurate and reliable so that in a court jury, a correct decision can be made. Thus, the mode of data collection is as important as the data collected.

3.1.2 Processing Layer

The processing layer is where the collected raw data in the data acquisition layer can be processed and reviewed. Here, raw data is then analysed and converted into relevant information which can be used in court to make a verdict [43]. In this layer, crime scene investigators can observe and pinpoint the chain of events that transpired during a specific crime scene. Several observations can be made at this point such as:

- Identification of potential suspects

- Modus operandi used
- Mapping of evidence at the crime scene
- Apprehension of prime suspects

3.1.3 Decision Support Layer

The final layer depicts the decision support layer. In this layer, collected crime scene information can be presented and thoroughly evaluated by a jury in court, and a final verdict can be made based on the statements documented and the supporting information [54]. In summary, the evidence is useful in various ways, which include:

- Better attribution of past crimes
- Fair and consistent sentencing by the jury
- Identification of potential suspects
- Criminal profiling and discovery of serial crime
- Determination of mitigation priorities

3.2 Research Focus and Approach

While Figure 3.1 presents an overall framework for a crime scene data solution, the focus of this research is to explore a potentially low-cost solution for 3D crime scene data gathering. Therefore, this research focuses on the data acquisition layer of this framework. The motivation is the fact that crime scene investigators in low-resource settings, such as Africa, often do not have access to existing high-end solutions for 3D crime scene data collection due to resource constraints. This was also confirmed by crime scene experts in South Africa in an interview conducted. Furthermore, the application of immersive technology in forensic science is yet to fully permeate the field. Hence, this research conducted an exploratory study which considered three (3) major factors. Ten mobile devices spanning ARKit and ARCore frameworks were utilized for the experiment. The major factors explored are:

(i) AR Measurements

(ii) Plane detection

(iii) Resource (CPU/RAM) Utilization

To facilitate and evaluate these three (3) major factors, certain hardware and software components were utilized as shown in Tables 3.1 and 3.2. Furthermore, a prototype application was then developed using the best performing devices based on empirical observations on the performance of the devices.

Table 3.1: Hardware tools.

Hardware	**Description**
iPad Pro 5th Gen	This mobile device was used for its LiDAR scanner, it also stored scanned 3D crime scene data as well as house the experimental low-cost AR application.
Apple Mac mini	The Apple Mac mini was used to develop the experimental mobile AR application. All the mentioned software tools were used on this device besides the Vuforia® engine v10 software. The specifications of this computer are: macOS Monterey, Intel core i5 dual core processor, 8GB of random-access memory (RAM) and Intel HD Graphics 5000.
Tape measure	A generic tape measure was used as a control to set out criteria measurements for the three major evaluated factors. This tape measure was also used to compare the measurement accuracy of the LiDAR scanned 3D data obtained from the iPad Pro 5th Gen.
Windows desktop computer	The Windows desktop PC was used for the development and deployment of the ARCore application to all the ARCore / Samsung mobile devices. The specifications of this device are: Windows 10 Pro version 22H2 with a 6 core, 12 thread Ryzen 5 1600 with 32GB of RAM.

Table 3.2: Software tools.

Software	**Description**
Adobe XD	This software application was used to brainstorm and draft the mobile AR application's wireframe. The wire-frame prototype encompassed the user interface (UI) navigation and design.
Microsoft Word	This application was used to document items of importance such as application objections, problems, observations, and solutions to aforementioned problems.
Microsoft Excel	This data processing application was used to record tabular data of importance such as captured experimental application metric data.
Microsoft Visio	This data visualization application was used to plot out relevant diagrams applicable for the experimental application's development such as the flowcharts contained in this thesis work.
Vuforia® engine v10	This application was used in combination with the LiDAR scanner on the iPad Pro 5th Gen to capture 3D data in the hypothetical crime scenes.
Unity® Version. 2022.1.22	This application was used for the development of the prototype mobile AR application. This application (Unity® Version. 2022.1.22) housed the prototype's entire UI, backend scripts and the overall functionality.
Visual Studio	This application was used to write the backend C# programming code which enabled functionality for the developed mobile applications, see Appendix A for additional C# code examples.
Xcode v14	This software application was used to deploy developed ARKit applications to all the ARKit running devices such as the iPhone Xr, iPhone 8 etc.

3.2.1 Data Collection: Platform For the 3D Data Collection Environment

Considering that the purpose of this research is to explore a low-cost solution for 3D crime scene data collection, two hypothetical crime scenes were used to collect 3D data, which are (i) an indoor hypothetical crime scene and (ii) an outdoor hypothetical crime scene. The reason why two hypothetical crime scenes were used, and not actual crime scenes is due to the fact that this research was solely based on an exploration for a low-cost solution and there are ethics constraints associated with real crime scenes.

Ten mobile devices were used in testing the three major factors. The mobile devices are, the Samsung A20 Samsung A32, Samsung S8, Samsung S10, Samsung S20, iPhone 8, iPhone Xr, iPhone 11, iPhone 11 Pro and the iPad Pro 5th Gen. These ten mobile devices were split evenly across two AR frameworks, ARKit and ARCore. All the Samsung devices represented ARCore and all of the iPhone devices including the iPad represented ARKit as seen in Table 3.3. The reason these ten mobile devices were utilised is because they offer the greatest variation in terms of age (i.e., roll-out history). Age variation refers to the comparison of older devices e.g. Samsung S8 compared to S20. Furthermore, the consideration to use mobile devices is due to the fact that they are more cost effective in comparison to more sophisticated high-end tools for AR related applications such as plane detection and AR measurements. Hence, this research explored the potential trade-offs (costs) that might be associated with using these alternatives under certain parameters and conditions. Table 3.4 depicts the ten devices used in testing as well their specification configuration layout.

Table 3.3: Utilized AR framework amongst ten devices

Device	AR Framework Utilized
iPhone Xr	ARKit
iPhone 11 Pro	ARKit
iPhone 8	ARKit
iPhone 11	ARKit
iPad Pro 5th Gen	ARKit
Samsung S8	ARCore
Samsung S20	ARCore
Samsung S10	ARCore
Samsung A20	ARCore
Samsung A32	ARCore

Table 3.4: Specification layout of the devices used.

Device	Processor ID	Core count	Camera specifications	RAM capacity
iPhone Xr	A12 Bionic	6	12 MP, f/1.8, 26mm (wide), 1/2.55", 1.4μm, PDAF, OIS	3GB
iPhone 11 Pro	A13 Bionic	6	12 MP, f/1.8, 26mm (wide), 1/2.55", 1.4μm, dual pixel PDAF, OIS 12 MP, f/2.0, 52mm (telephoto), 1/3.4", 1.0μm, PDAF, OIS, 2x optical zoom 12 MP, f/2.4, 120°, 13mm (ultrawide), 1/3.6"	4GB
iPhone 8	A11 Bionic	6	12 MP, f/1.8, 28mm (wide), PDAF, OIS	2GB
iPhone 11	A13 Bionic	6	12 MP, f/1.8, 26mm (wide), 1/2.55", 1.4μm, dual pixel PDAF, OIS 12 MP, f/2.4, 120°, 13mm (ultrawide), 1/3.6"	4GB
M1 iPad Pro 5th Gen	M1	8	12 MP, f/1.8, (wide), 1/3", 1.22μm, dual pixel PDAF 10 MP, f/2.4, 125° (ultrawide) TOF 3D LiDAR scanner (depth)	8GB
Samsung S8	Exynos 8895	8	12 MP, f/1.7, 26mm (wide), 1/2.55", 1.4μm, dual pixel PDAF, OIS	4GB
Samsung S20	Exynos 990	8	12 MP, f/1.8, 26mm (wide), 1/1.76", 1.8μm, Dual Pixel PDAF, OIS 64 MP, f/2.0, 29mm (telephoto), 1/1.72", 0.8μm, PDAF, OIS, 1.1x optical zoom, 3x hybrid zoom 12 MP, f/2.2, 13mm, 120° (ultrawide), 1/2.55" 1.4μm, Super Steady video	8GB
Samsung S10	Exynos 9820	8	12 MP, f/1.5-2.4, 26mm (wide), 1/2.55", 1.4μm, Dual Pixel PDAF, OIS 12 MP, f/2.4, 52mm (telephoto), 1/3.6", 1.0μm, AF, OIS, 2x optical zoom 16 MP, f/2.2, 12mm (ultrawide), 1/3.1", 1.0μm, Super Steady video	8GB
Samsung A20	Exynos 7884	8	13 MP, f/1.9, 28mm (wide), AF 5 MP, f/2.2, 12mm (ultrawide)	3GB
Samsung A32	Helio G80	8	64 MP, f/1.8, 26mm (wide), PDAF 8 MP, f/2.2, 123°, (ultrawide), 1/4.0", 1.12μm 5 MP, f/2.4, (macro) 5 MP, f/2.4, (depth)	4GB

The chosen AR frameworks of choice are ARCore and ARKit. The reason these two AR frameworks are considered is due to the fact that the most dominant mobile operating systems (OS) are Android and iOS [37]. The Android OS is provided by Google and the iOS OS is provided by Apple. Google and Apple manufacture ARCore and ARKit respectively. Both AR frameworks offer similar features; however, they may not necessarily always achieve the same level of accuracy and reliability in certain applications. Table 3.5 depicts the different capabilities supported by each AR framework plugin applicable for the testing. Supported features are indicated with a tick symbol (✓), while those not supported are indicated with a cross symbol (X).

Table 3.5: Summary of supported features in both frameworks.

Supported Feature	ARCore	ARKit
Device tracking	✓	✓
2D Image tracking	✓	✓
3D Object tracking	X	✓
Occlusion	✓	✓
LiDAR meshing	X	✓
Raycast	✓	✓
Plane tracking	✓	✓
Anchors	✓	✓
Light estimation	✓	✓

Two structural mobile applications were developed on the latest ARKit and ARCore Software Development Kit (SDK) pluggins (5.0.2) for Unity version 2022.1.22. These two mobile applications shared the exact code and features, the only variation was with the AR frameworks. AR Foundation version 5.0.2 was used for plane detection. Visual studio 2021 was used for the backend C# code. The backend code handled the core functionalities i.e., calculations etc. The ARKit version of the application was developed on the Apple Mac mini, while the ARCore version was developed on the Windows desktop. These tools for development (Apple Mac mini and Windows desktop) are listed in the aforementioned hardware tools in Table 3.1 with their specifications. Xcode 3.2 was used to deploy and monitor RAM and CPU usage of all the ARKit devices. For all the ARCore running devices Android studio was used as shown in Figure 3.2.

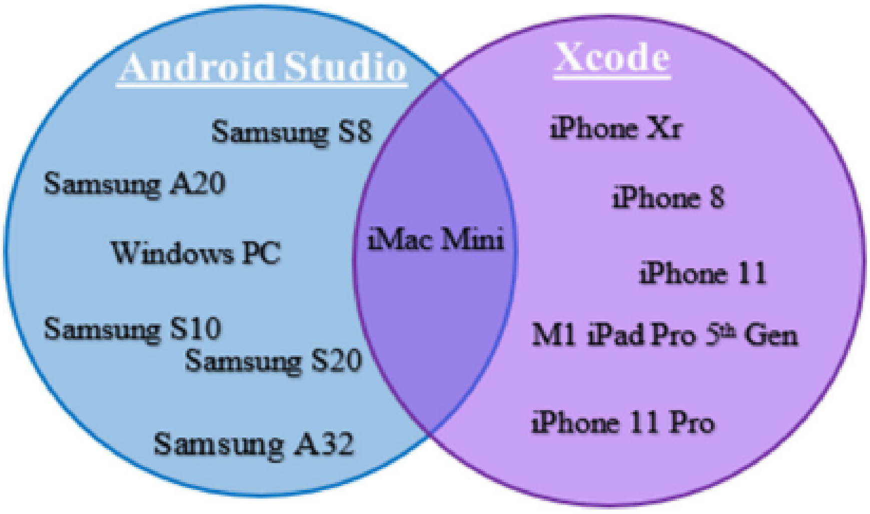


Figure 3.2: Overall software and mobile devices compatibility.

3.2.2 AR Measurements: Based on ARKit and ARCore Mobile Devices

Traditional methods of crime scene measurement usually involve using a measuring tape [90], [102]. However, potential risks of limitations have been identified such as the bending or flexing of tape, which could result in an inaccurate reading [5]. The use of a measuring tape in less ideal conditions of a crime scene could result in what is referred to as scene contamination [11], [103]. Hence, AR measurements could be an alternative to avoid some of these limitations.

Two structural applications were developed to evaluate AR measurements conducted between the ten mobile devices running ARKit and ARCore, see Figure 3.3. A tape measure was used as a control to set the different measurement criteria. A crime scene scenario was used where the distance between two items within the crime scene represents either point A or B as illustrated in Figure 3.4. The accuracy of both AR frameworks were evaluated based on how close they could get to the control value. Six test runs were conducted across all four measurement criteria, which are (i) "10cm", (ii) "45cm", (iii) "75cm" and (iv) "100cm" taken from a distance of one meter (1m) and two meters (2m) across all tests as shown in Figure 3.5.

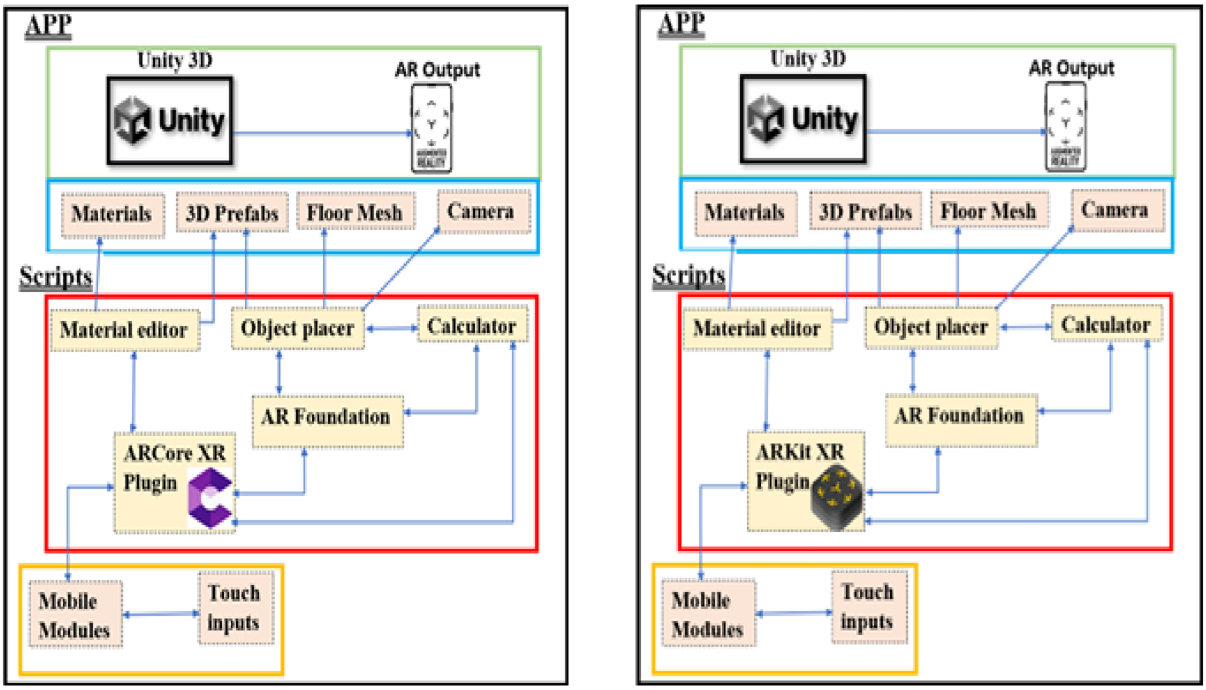


Figure 3.3: ARCore (left) and ARKit (right) application layout.

Figure 3.6 illustrates the background pseudocode processes involved in acquiring AR measurements. The pseudocode instantiates three variables named "planeDetection", "pointCounterPlacement" and "measureDistance", and assigns them all with a value of 0. The application starts by detecting planes, hence, the variable "planeDetection" is auto incremented by one (1) (planeDetection++). A While loop checks whether a single or multiple planes have been detected, if one or more planes have been detected then a user my start making AR measurements (pointCounterPlacement++). A nested IF statement commences verifying whether two or more AR measurement points have been made (IF pointCounterPlacement >=2). If two or more AR measurement points have been made then the distance been those points is calculated and the result is printed on screen (Print measureDistance). Once the distance has been printed all values return back to 0.

The evaluation averages were computed using Equation (3.1) to acquire the average score ($\overline{\mathrm{D}}$) of each device (D) after six test runs per criteria.

$$\overline{\mathrm{D}} = \frac{1}{N}\Sigma_{j=1}^{N}X_j \tag{3.1}$$

Where N represents the total number of test runs that was conducted for each device (D) per distance

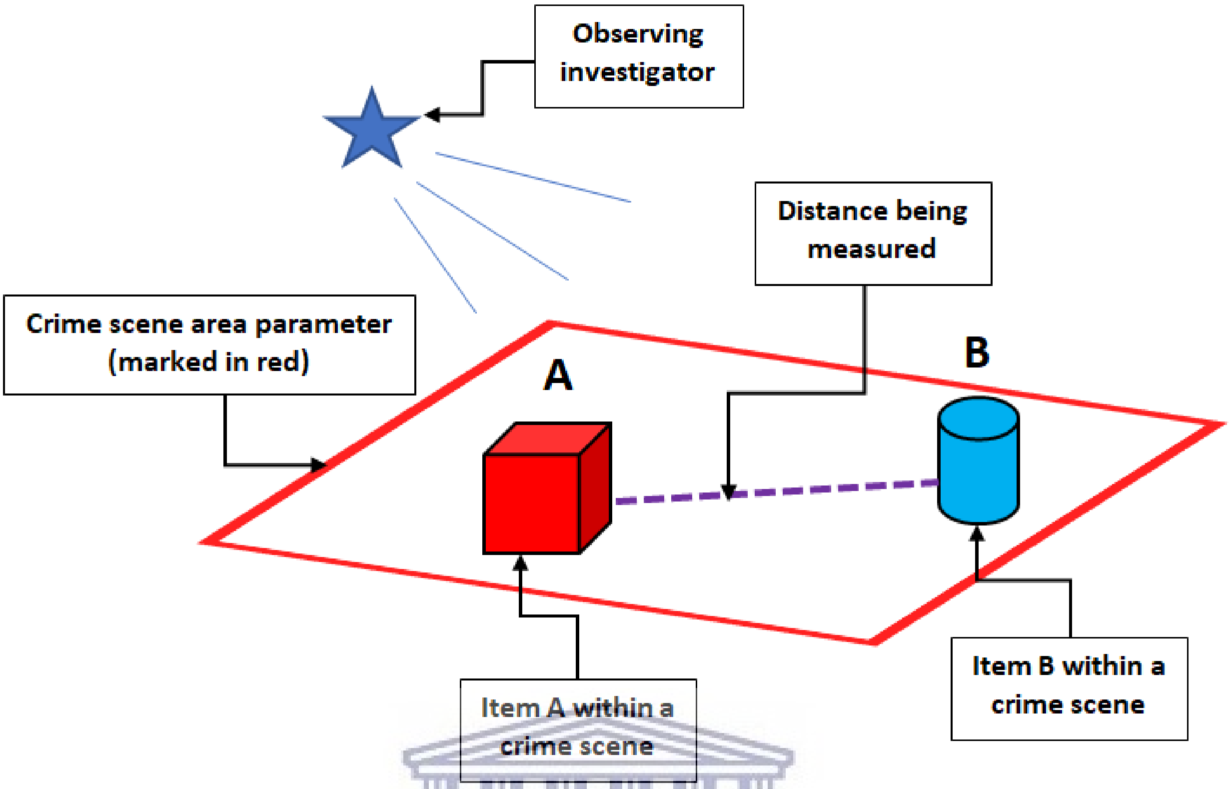


Figure 3.4: Depiction of distance measured at a crime scene.

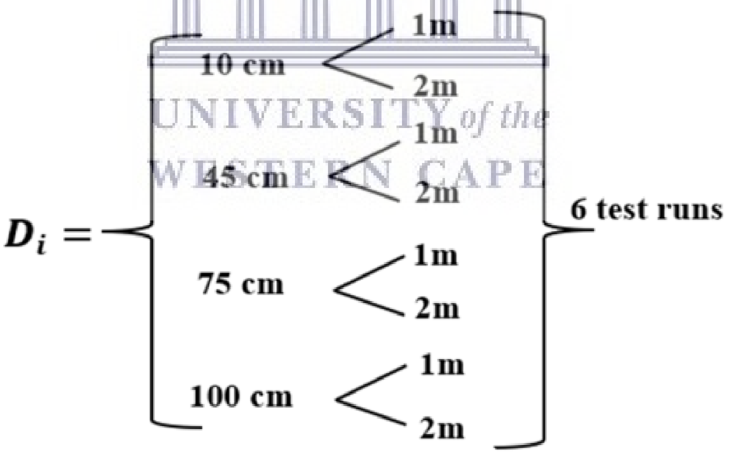
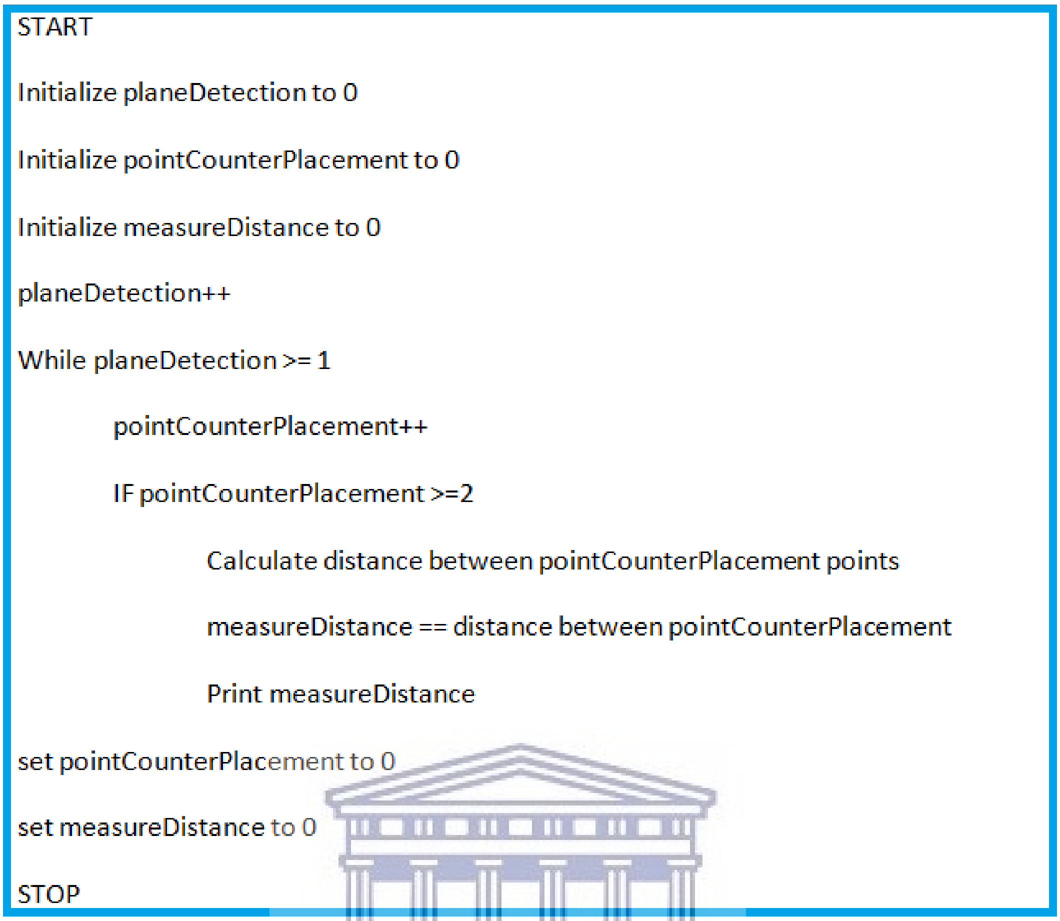


Figure 3.5: Depiction of the four (4) distance criteria used at 1m and 2m observation points with 6 test runs for each device.

criterion. Parameter X represents the measured distance between two points (A and B) per time per test for each D.



```
START
Initialize planeDetection to 0
Initialize pointCounterPlacement to 0
Initialize measureDistance to 0
planeDetection++
While planeDetection >= 1
        pointCounterPlacement++
        IF pointCounterPlacement >=2
                Calculate distance between pointCounterPlacement points
                measureDistance == distance between pointCounterPlacement
                Print measureDistance
set pointCounterPlacement to 0
set measureDistance to 0
STOP
```

Figure 3.6: AR measurement pseudocode.

3.2.3 Plane Detection: Horizontal and Vertical Mapping

AR frameworks work with mobile cameras in determining and detecting geometric planes using the parallax concept to determine depth. The parallax concept measures the angle of inclination between two lines by means of calculating the difference or displacement of an apparent object viewed along two unrelated lines of sight [104]. Figure 3.7 presents a mobile device video camera, a user would normally move the video camera around to acquire a “left eye” and “right eye” view (i.e., different lines of sight) to record surfaces. Through the utilization of a mobile camera, the AR frameworks can record and acquire the different inclination angles between the two eye views through the parallax concept, thus enabling plane detection.

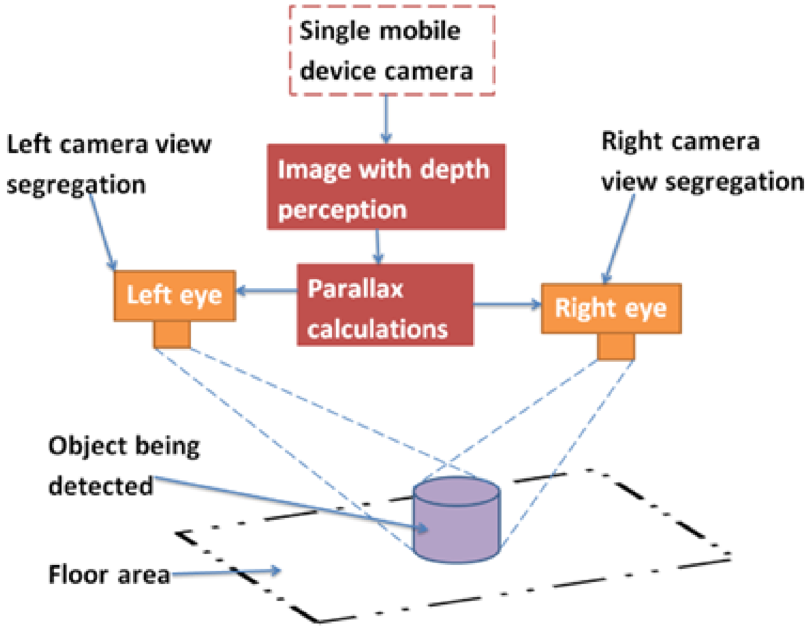


Figure 3.7: Schematic diagram of AR depth plane detection.

The evaluation of this criteria was the detection of horizontal and vertical planes under two different lighting conditions. The first lighting mode was under 40-watts of ambient lighting and the second was under 14-watts of ambient lighting. The ip20 Dali dimmer strips, which controls the level of illumination, were used in testing, and they offered a maximum illumination brightness of 40-watts and minimum illumination brightness setting of 14-watts, hence, the use of these two distinct lighting modes. This test was meant to compare how the two AR frameworks, ARKit and ARCore, perform when it comes to light estimation and plane detection under different lighting conditions. These tests were also timed with a stopwatch to determine whether there was a time variation in plane detection under different lighting conditions.

For the evaluation, two mobile AR plane detection applications were developed to access how the two AR frameworks handle horizontal and vertical plane detection. These applications were developed using the latest versions of ARCore and ARKit to determine the best viable option for diverse augmented reality mapping and plane detection solutions.

3.2.4 Resource (CPU and RAM) Utilization

This test criteria evaluated and compared the efficiency of ARKit and ARCore with respect to RAM and CPU usage whilst using the mobile AR applications. For each mobile device, a CPU idle check was conducted ten minutes after a clean reboot, with no background running applications, besides the operating system and the important service applications. Later, the two aforementioned mobile AR applications were ran, ten minutes into running the applications, CPU average load percentages were captured for evaluation. Xcode was used to verify this data for all the ARKit running devices and CPU profiler was used to verify this data for all ARCore running devices. Data acquired from these tests was then compared to verify the relative change. Equation (3.2), was used to compute the relative change spanning all ten mobile devices. Tests conducted do not consider the different CPU architectures, RAM management and the nanometer fabrication processes spanning these ten devices. CPU architecture, refers to the data path integer width a processor can work with, normally expressed as 32-bit (x86) or 64-bit. Nanometer fabrication process refers to CPU node size which is measured in nanometers (1×10^{-9} m) .

$$Rc = \frac{X_2 - X_1}{X_1} \tag{3.2}$$

Where Rc is the final relative change, X_2 represents the final value, while X_1 is the initial value.

3.2.5 Development of Prototype for 3D Crime Scene Data Collection

Based on empirical observations on the three major factors spanning ten mobile devices, the device with the best performance was used to further develop a prototype application. These empirical observations covered AR measurements based on the four aforementioned distance criteria, (i) "10cm", (ii) "45cm", (iii) "75cm", (iv) "100cm", horizontal and vertical plane detection and resource (CPU/RAM) utilization across all ten mobile devices. The prototype application evaluated the following criteria:

(A) Quality of 3D scanning using the utilization of a LiDAR scanner

(B) AR measurements on the iPad Pro 5th Gen Mobile Device

(C) 3D scanned scenes localization re-visitations

Figure 3.8 depicts the schematic UI navigation design for the developed prototype application.

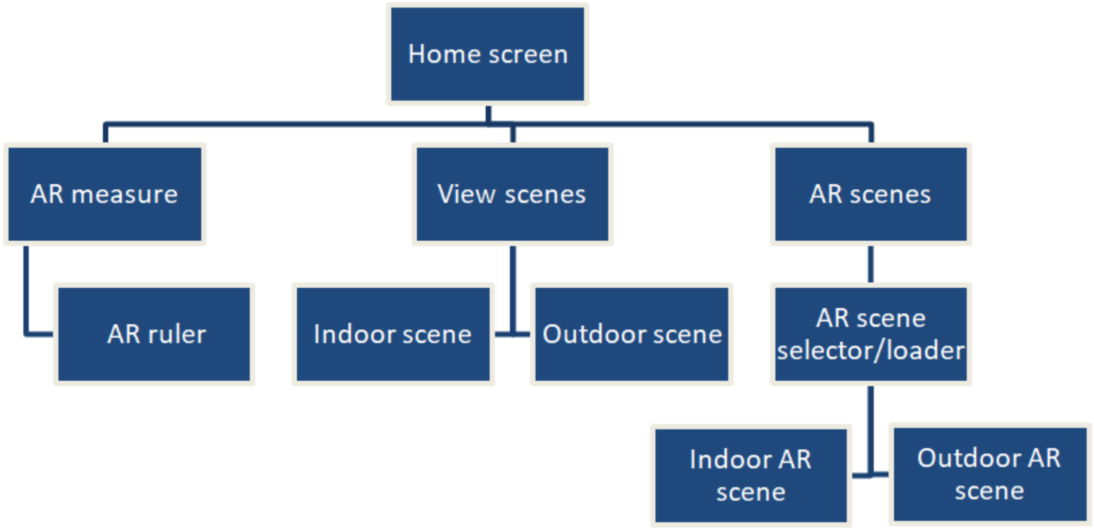


Figure 3.8: Prototype mobile AR application UI navigation layout.

The application UI navigation starts from the "Home screen", here, a user meets the main landing page / home screen of the application. From the "Home screen" the application has three (3) sub-menus titled (i)"AR measure", (ii)"View scenes" and (iii)"AR scenes". Within the "AR measure" sub-menu a user is able to start conducting AR measurements. Pressing on the "View scenes" button leads to a sub-menu containing two 3D hypothetical crime scenes which are; (i) Indoor scene and (ii) Outdoor scene. This section allows a user to move around the scenes as if there are physically present using a navigation tool built into the prototype application. Pressing on the "AR scenes" button from the Home screen leads to a sub-menu containing the same two aforementioned hypothetical crime scenes however, in this scenario those scenes are augmented and contain AR information overlay of POI. Figure 3.9 depicts the application layout for the developed prototype application.

(A) 3D scanning: using the utilization of a LiDAR scanner

For 3D scanning, two hypothetical crime scenes were utilized to acquire 3D crime scene data using a LiDAR scanner housed on the iPad Pro 5th Gen and the Vuforia® Area Target Creator. The Vuforia® Area Target Creator is an application which enables the use and storage of 3D data acquired from the iPad Pro 5th Gen's LiDAR scanner. It permits for 3D scanned data to be securely stored in fragments on the iPad Pro 5th Gen and backed up online on a database. Scans obtained are securely brought into Unity® with a 380-character linking password between

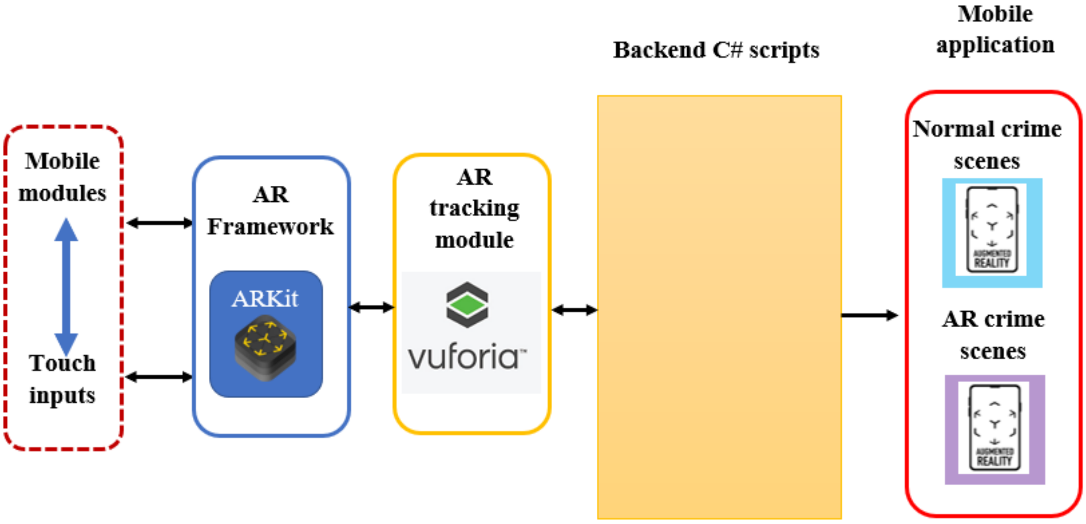


Figure 3.9: AR application layout.

Vuforia® and the iPad Pro 5th Gen. Unity®, an aforementioned software in Table 3.2 is a game engine used for the low-cost solution prototype development and deployment.

These crime scenes both measured four (4) meters in length and four meters (4) in breadth, giving an area of 16 meters squared as shown in Figure 3.10. The area selection of 16 meters was chosen based on feedback provided by professional experts in crime scene investigations. The reason why an indoor crime scene and an outdoor crime scene was used is to assess how the LiDAR scanner performs under two different lighting conditions. Multiple generic items were scattered in both crime scenes, which contained the same amount of the following items:

- 1 x Knife
- 2 x Wine opened bottle
- 1 x Cigarette
- 1 x Wine cap
- 2 x Shoes

The evaluation metrics of this criteria are twofold, firstly, the scanned crime scenes are evaluated by means of visual quality and integrity, integrity refers to the accuracy measurements of items within a scanned scene. Secondly, time was evaluated by means of calculating the time span difference taken to scan the indoor crime scene and outdoor crime scene using Equation (3.2) to obtain the relative time change.

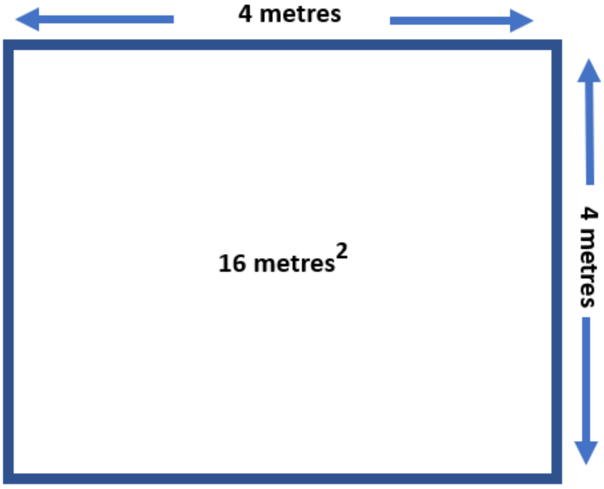


Figure 3.10: Crime scene area measurement.

(B) AR measurements: on the iPad Pro 5th Gen Mobile Device

A structural application was built to evaluate AR measurements conducted on the iPad Pro 5th Gen. A tape measure was used as a control to set the different measurement criteria. This test criteria assessed the reliability and accuracy of the AR measurements obtained. Six test runs were conducted per control criteria. Eight measurement criteria were used, which are “10cm”, “45cm”,“75cm”, “100cm”, ”200cm”, ”300cm”, ”400cm” and ”500cm” at a distance of one meter and two meters across all tests. To determine the error margins, Equation (3.1) was used to compute the averages across all tests after 6 test runs. Figure 3.11 shows the distance criteria used with six test runs on the iPad Pro 5th Gen.

(C) 3D scanned scenes: Localization re-visitations

Using the two aforementioned scanned 3D indoor and outdoor hypothetical crime scene data, this section evaluated whether localized 3D data within an already scanned environment could still be augmented. Augmented referring to superimposing computer generated points of interest (POI) providing information overlay for investigators. This test verifies that if localization can occur after a crime scene has been cleared then the placement of AR information overlay, and POI should be accurate and reliable for a jury court.

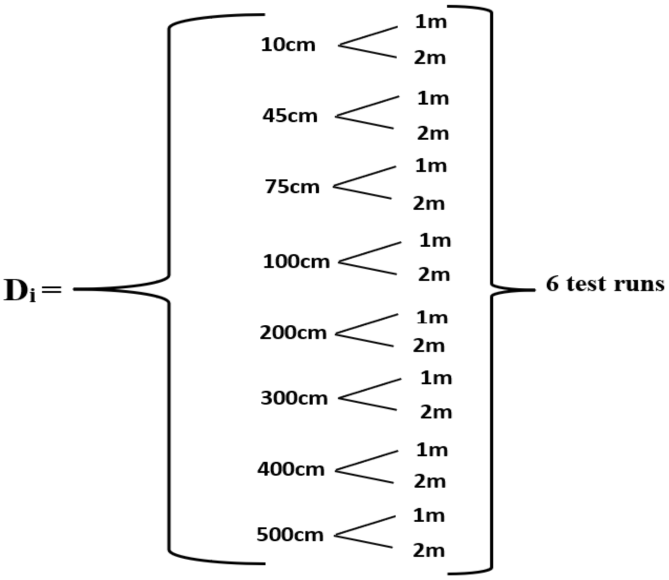


Figure 3.11: Depiction of distance criteria used with 6 test runs: iPad measurements.

3.3 Chapter Summary

The discussion in this chapter presents a general overview of the methodology, namely the 3D Crime Scene Data Solution Framework, which acts as a trinity to crime scene investigations, the design structure and approach of this methodology. This methodology consists of the application development schematics, test setups, evaluation metrics and tools utilized in development. This methodology was broken up into two sections, the first section evaluated the three major factors those being (i)AR measurements, (ii) Plane detection and (iii) Resource (CPU/RAM) utilization. Based on empirical findings, the mobile device with the best performance was used to further develop a prototype application.

Chapter 4

RESULTS, DISCUSSIONS AND EXPERIMENTAL EVALUATION

To establish the reliability or effectiveness of the proposed low-cost solution approach to 3D crime scene data gathering, experimental results are presented in this chapter. The results and discussions section is broken up into two sections, section one presents the findings based on three major factors spanning ARKit and ARCore across ten mobile devices. Based on the empirical observations, section two further expanded on the research and developed a prototype application using the device (iPad Pro 5th Gen) with the most promising results, which evaluated the (i) Quality of 3D scanning, based on the utilization of a LiDAR scanner, (ii) AR measurements, and (iii) 3D scanned scenes: localization re-visitations. This chapter explores whether the developed low-cost solution prototype is applicable for 3D crime scene investigations in terms of accuracy and reliability.

4.1 Sample Crime Scene Environment

In order to facilitate the required experiment for this research, two (2) hypothetical crime scenes were utilized to determine the measurement accuracy and reliability between the two AR frameworks considered, ARKit and ARCore. The hypothetical crime scenes utilized scattered items such as:

- Knife
- Wine opened bottle

- Cigarette
- Wine cap
- Shoes

The hypothetical crime scenes measured four (4) meters in length and four meters (4) in breadth, results in an area of 16 meters squared. A generic tape measure was used as a control to set out the different measurement criteria. Two different lighting conditions were utilized within these hypothetical crime scenes to evaluate how these AR frameworks handle light estimation and plane detection. Figure 4.1 provides a sample crime scene used in testing.

Figure 4.1: Sample crime scene: Indoor hypothetical crime scene.

4.2 Empirical Observations on Experimental Data

Three major criteria were explored using ten mobile devices, spanning ARKit and ARCore. These criteria are;

- AR measurement

- Plane detection
- Resource (CPU/RAM) utilization

4.2.1 AR Measurements: Based on ARKit and ARCore Mobile Devices

Two mobile applications were developed to evaluate AR measurements conducted between the ten mobile devices running ARKit and ARCore. A tape measure was used as a control to set the different measurement criteria. The measurement criteria utilized within the AR measurements are (i)“10cm”, (ii)“45cm”, (iii)“75cm” and (iv)“100cm” taken from a distance of one meter (1m) and two meters (2m) respectively across each test. A hypothetical crime scene scenario was used where the distance between two items within that crime scene represented either point A or B. Figure 4.2 depicts a tape measure setup for the ”100cm” criteria, however, the AR measurement in this scenario had a slight deviation and measured ”99cm”. The accuracy of both AR frameworks were evaluated based on how close they could get to the control value. Six test runs were conducted across all four measurement criteria as earlier depicted in Figure 3.5 and section 3.2.2.

Figure 4.2: Sample AR measurement measuring 100cm.

To ensure fairness, the 1-meter and 2-meter marks were kept consistent for each distance criteria tested. There were also equal numbers of devices used for each AR framework (5 for ARKit and ARCore). These devices also equally vary in terms of roll out history.

Table 4.1 depicts raw data captured by the ten mobile devices spanning ARKit and ARCore. The raw data depicts the 75cm test criteria taken from 1 meter away. After applying Equation (3.1) we get the computed average accuracy values for each of the two AR frameworks spanning all ten mobile devices. The overall average for each framework was then computed based on each distance criteria and test runs. The first row represents the control (tape measure), hence, the denotation of N/A readings. Empirical observations based on this single criteria show that the iPad Pro 5th Gen performed the best on average in this set criteria and the iPhone Xr performed the worst on average for this specific criteria.

Table 4.1: AR 75CM measurements taken from 1 meter away.

Device Name	Result 1 (CM)	Result 2 (CM)	Result 3 (CM)	Result 4 (CM)	Result 5 (CM)	Result 6 (CM)	Average (CM)	Best Result (CM)	Worst Result (CM)
Tape measure	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**75**	**N/A**	**N/A**
Samsung S8	73	70	76	75	74	74	**73.67**	75	76
Samsung S10	73	74	73	76	74	73	**73.83**	74	76
Samsung S20	75	77	73	77	76	77	**75.83**	75	77
Samsung A20	74	76	74	73	74	75	**74.33**	75	76
Samsung A32	74	75	75	74	73	71	**73.67**	100	108
iPad Pro 5th Gen	72	76	74	74	75	76	**74.50**	75	76
iPhone Xr	69	73	72	71	74	74	**72.17**	74	69
iPhone 11 pro	81	73	75	73	72	65	**73.17**	75	65
iPhone 8	76	75	76	76	77	75	**75.83**	75	77
iPhone 11	73	73	72	75	73	72	**73.0**	75	72

Figures 4.3 and 4.4 present the comparative results of 10cm test taken from a distance of 1-meter and 2-meters respectively. Findings illustrate that 60% of the devices running either ARKit or ARCore improve in terms of accuracy at the 2-meter mark compared to the 1-meter mark. 30% of the devices retained the same accuracy average from the 1-meter and 2-meter mark. 10% of the devices decrease in average accuracy moving from 1-meter to 2-meters. The worst performing device in the 1-meter test

criteria was the Samsung S8 and the best performing device was the iPad Pro 5th Gen. The worst performing device in the 2-meter test criteria was the Samsung S10 and the best performing device was the iPad Pro 5th Gen.

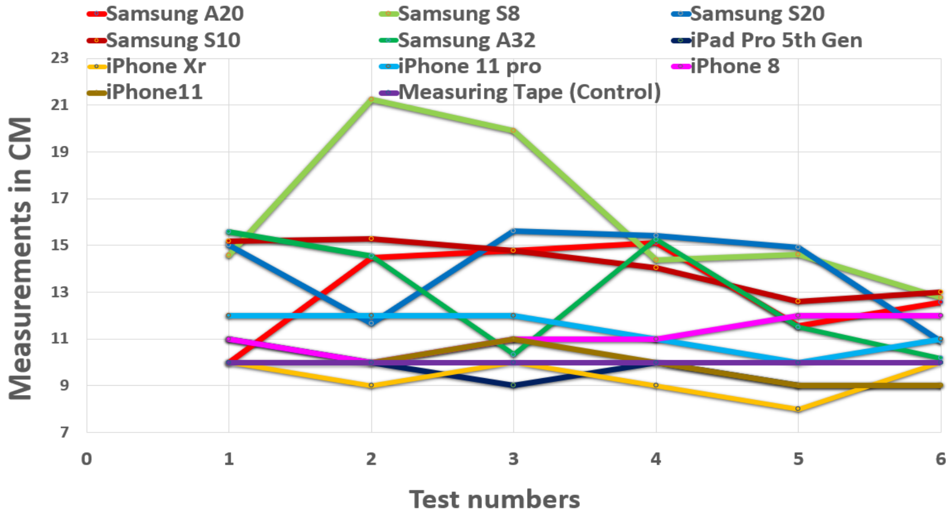


Figure 4.3: 10cm AR Measurements taken from 1 meter away.

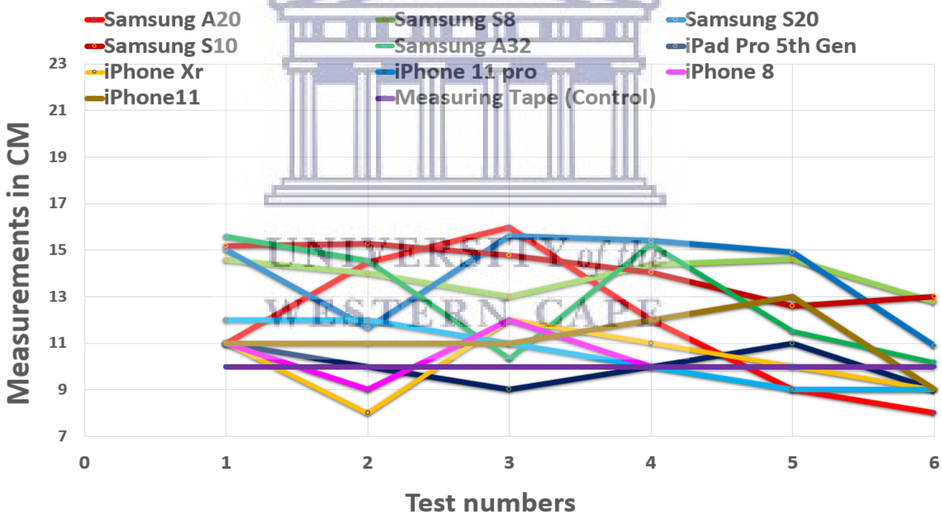


Figure 4.4: 10cm AR Measurements taken from 2 meters away.

Figures 4.5 and 4.6 show the 45cm criteria taken from a distance of 1-meter and 2-meters respectively. Findings show that 50% of devices running either ARKit or ARCore improve in terms of average accuracy at the 2-meter mark compared to the 1-meter mark. 40% of the devices decreased in average accuracy at the 2-meter mark compared to the 1-meter mark. Only 10% of the devices retained the same average accuracy at the 1-meter and 2-meter mark. The worst performing device in the 1-meter test criteria was the Samsung A20 and the best performing device was a three way tie between the iPad Pro 5th Gen, iPhone 11 and the iPhone Xr. The worst performing device in the 2-meter test criteria was the iPhone 11 and the best performing device was the Samsung S10.

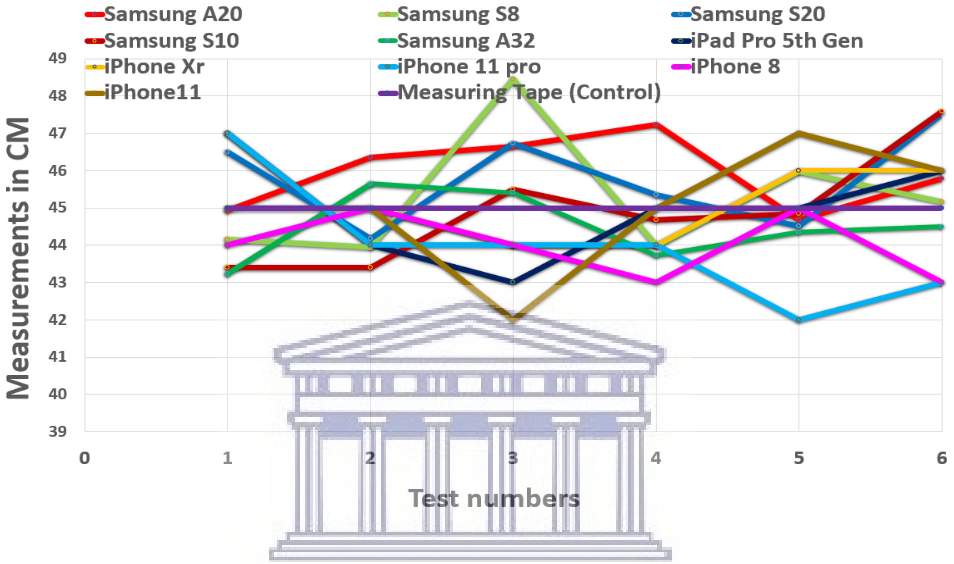


Figure 4.5: 45cm AR Measurements taken from 1 meter away.

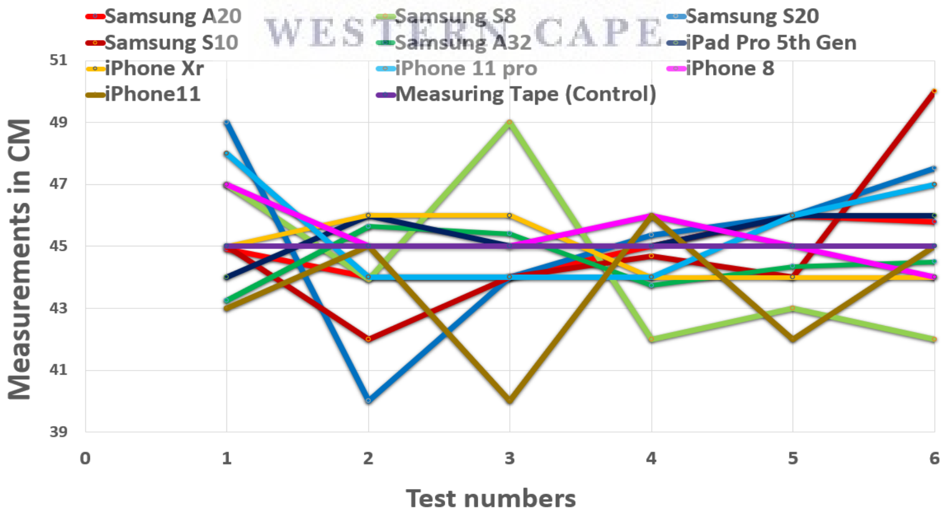


Figure 4.6: 45cm AR Measurements taken from 2 meters away.

Figures 4.7 and 4.8 show the 75cm criteria taken from a distance of 1-meter and 2-meters respectively. Findings show that 60% of devices running either ARKit or ARCore improve in average accuracy at the 2-meter mark compared to the 1-meter mark. 30% of the device decreased in average accuracy at the 2-meter mark compared to the 1-meter mark. Only 10% of the devices retained the same average accuracy at the 1-meter and 2-meter mark. The worst performing device in the 1-meter test criteria was the Samsung S20 and the best performing device was the iPad Pro 5th Gen. The worst performing device in the 2-meter test criteria was the iPhone 11 and the best performing device was the iPad Pro 5th Gen.

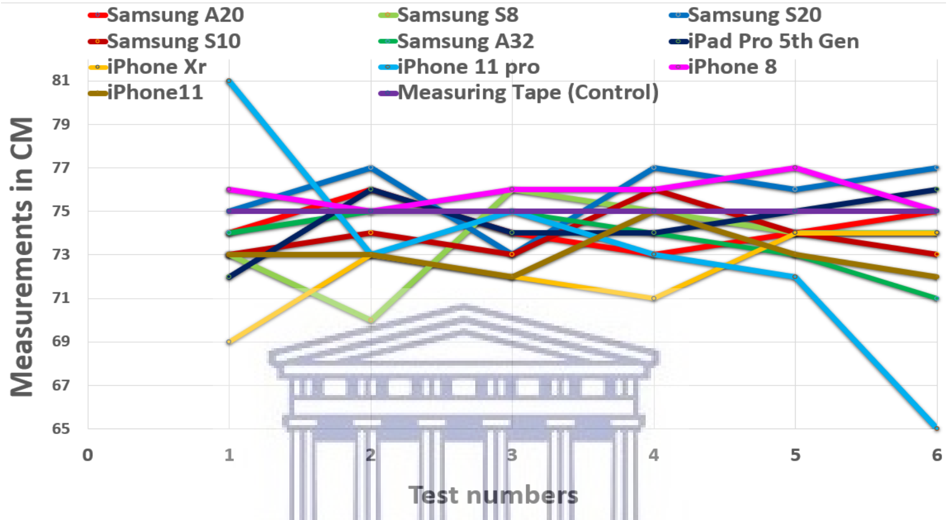


Figure 4.7: 75cm AR Measurements taken from 1 meter away.

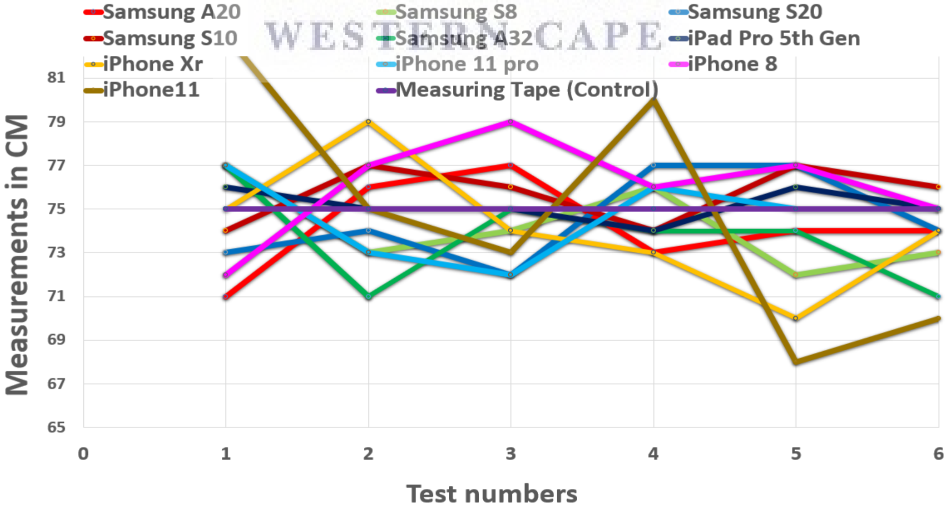


Figure 4.8: 75cm AR Measurements taken from 2 meters away.

Figures 4.9 and 4.10 show the 100cm criteria taken from a distance of 1-meter and 2-meters respectively. Finding show that 50% of devices running either ARKit or ARCore improve in average accuracy at the 2-meter mark compared to the 1-meter mark. The other 50% of the devices decreased in average accuracy at the 2-meter mark compared to the 1-meter mark. The worst performing device in the 1-meter test criteria was the Samsung S20 and the best performing device was the iPad Pro 5th Gen. The worst performing device in the 2-meter test criteria was the Samsung S20 and the best performing device was the iPad Pro 5th Gen.

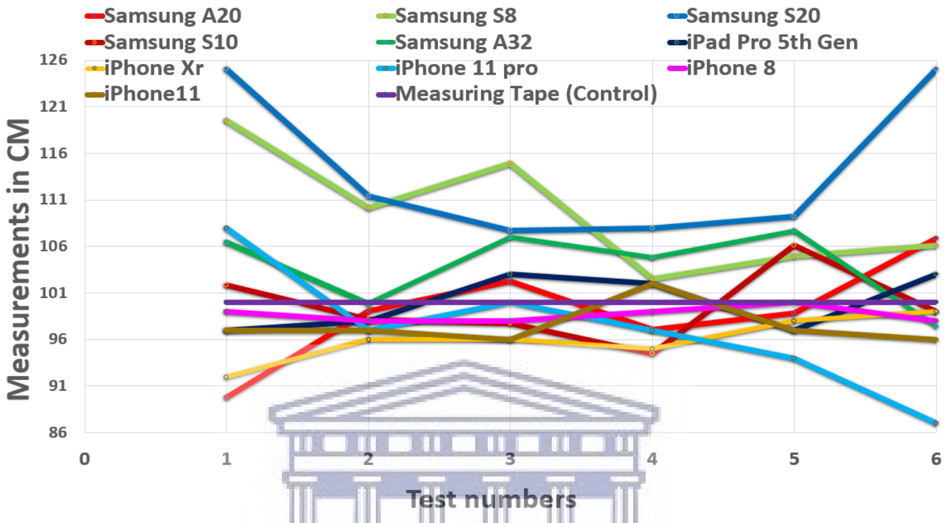


Figure 4.9: 100cm AR Measurements taken from 1 meter away.

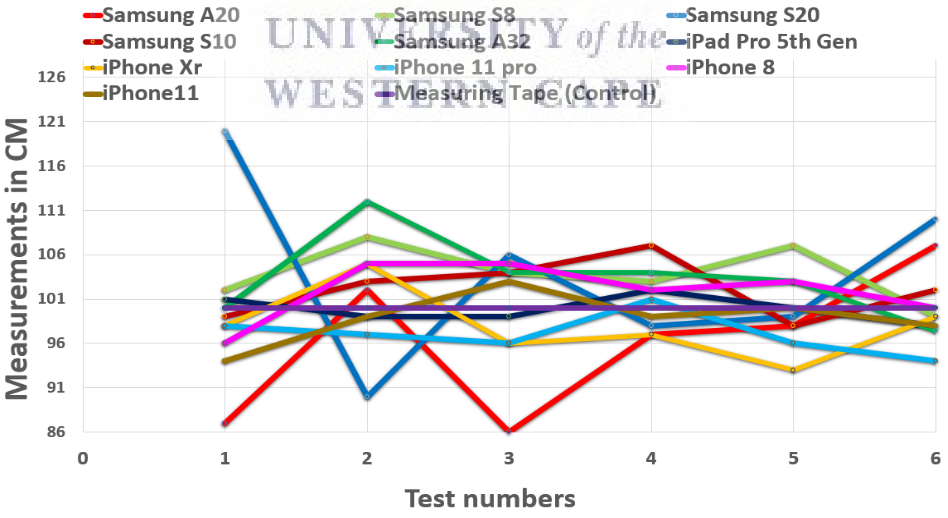


Figure 4.10: 100cm AR Measurements taken from 2 meters away.

The computed results show that in Figure 4.3 ARCore scored an average accuracy of 59.5% and ARKit scored an average accuracy of 92.67%. In Figure 4.4 ARCore scored 71.78% and ARKit scored 95.67%. In Figure 4.5 ARCore scored 99.38% and ARKit scored 99.11%. In Figure 4.6 ARCore scored 99.63% and ARKit scored 99.26% In Figure 4.7 ARCore scored 99.02% and ARKit scored 97.87%. In Figure 4.8 ARCore scored 99.24% and ARKit scored 99.33%. In Figure 4.9 ARCore scored 94.70% and ARKit scored 97.87%, while in Figure 4.10, ARCore scored 92.12% and ARKit scored 98.37%.

Table 4.2: Performance comparison of ARCore and ARKit.

Framework	Average accuracy score	Deviation
ARCore	89.42%	10.58%
ARKit	97.52%	2.48%

Table 4.2 depicts how the two AR frameworks, ARKit and ARCore, fared across all mobile devices when it came to the average accuracy. These results were obtained by averaging all the values obtained for Figures 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9 and 4.10 for each device per AR framework. Average results obtained from those Figures were then each divided by 5 to get the average accuracy for each framework. The final computed values are shown in this Table 4.2, results illustrate that ARKit is far superior than ARCore when it comes to accuracy and reliability in AR related applications within this specific context. ARKit performed better than ARCore in five out of the eight tests conducted.

4.2.2 Plane Detection: Horizontal and Vertical Mapping

Plane detection is critical for 3D scene mapping and reconstruction. AR frameworks work hand in hand with mobile cameras in determining depth by detecting and mapping horizontal and vertical planes. Mobile devices detect depth through the parallax concept as earlier discussed in section 3.2.3, this concept measures the angle inclination between two lines and calculates the difference or displacement of an apparent object viewed. For this test criteria, ten mobile devices were used in testing, two lighting modes were utilized, which are, 40-Watts and 14-Watts of ambient lighting. These lighting modes were utilized based on the maximum and minimum brightness levels offered by the ip20 Dali dimmer strips, which controlled the brightness/ dimmness in the test crime scenes. Figures 4.11 and 4.12 present the results obtained from both ARKit and ARCore running devices under the two lighting conditions while detecting planes in the hypothetical crime scene.

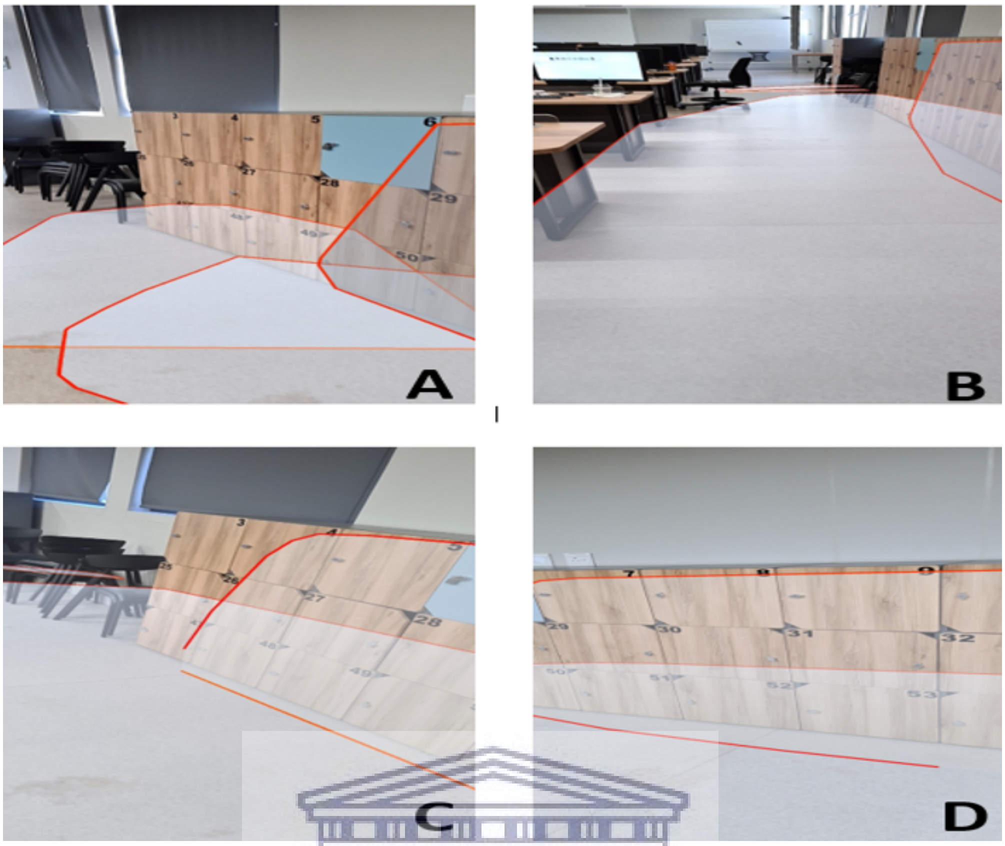


Figure 4.11: Sample plane detection images under 14-Watts (Best viewed in color mode).

In Figure 4.11, images labeled A and B represent two ARCore devices under 14-Watts of ambient lighting, C and D represent two ARKit running devices. In some instances, ARCore struggled to map out the test area correctly and at one stage had overlapping planes as shown in A. In Figure 4.12, images labeled E and F represent two ARCore devices under 40-Watts of ambient lighting, G and H represent two ARKit running devices. In this test case scenario, both AR frameworks excellently mapped out the entire test area. Minor alignment issues were noted for both ARKit and ARCore running devices as seen in Figure 4.12 images labeled E and G. These tests were also timed with a stopwatch to determine whether there was a time variation in plane detection and mapping under the different lighting conditions.

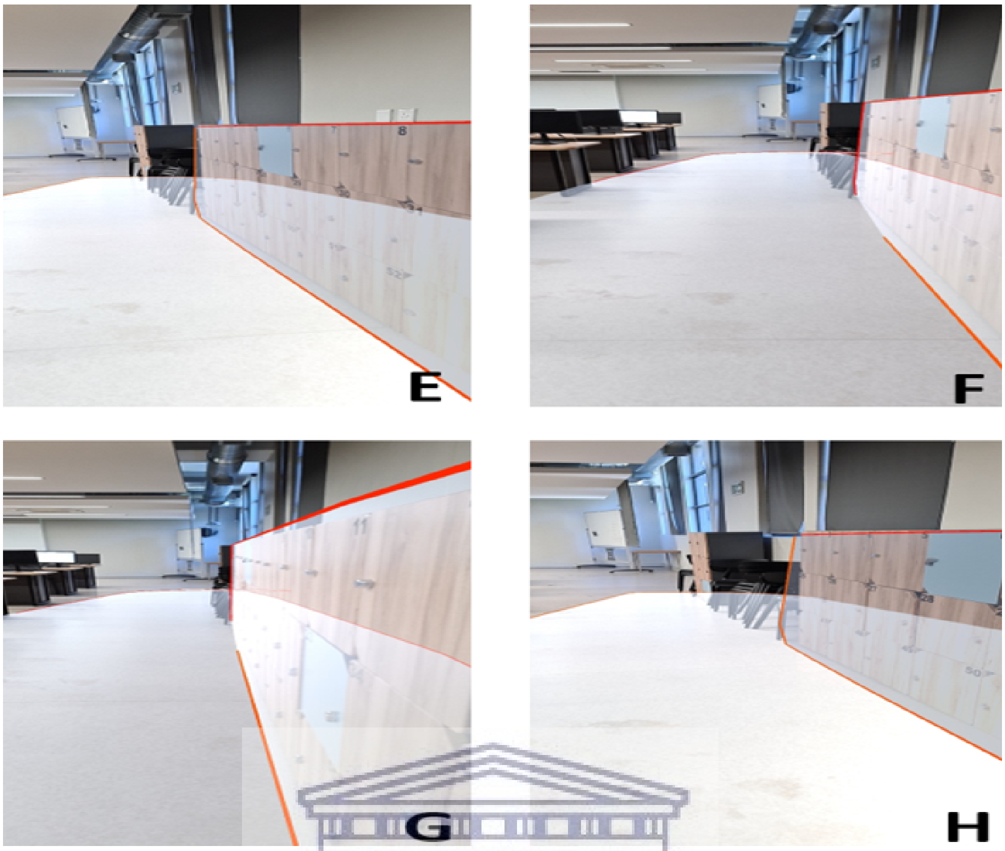


Figure 4.12: Sample plane detection images under 40-Watts.

Figure 4.13 draws the comparison of the time taken under 40-Watts and 14-Watts. This test was primarily geared towards the comparison on how the different AR frameworks cater to light estimation and plane tracking. Under 40-Watts of ambient lighting, all ten mobile devices substantially performed better when it came to detecting planes compared to 14-Watts of ambient lighting. Hence, in Figure 4.13 the term "Good lighting" represents 40-Watts of ambient lighting while "Bad lighting" represents 14-Watts of ambient lighting. Under good lighting, the iPad Pro 5th Gen device took the least amount of time to detect planes and map out the test crime scene. On the other hand, the Samsung S8 took the longest time to detect the same scene. Under bad lighting, the iPad Pro 5th Gen took the least amount of time again, while the iPhone 11 Pro took the longest amount of time out of all the other devices to detect and map out the hypothetical crime scene.

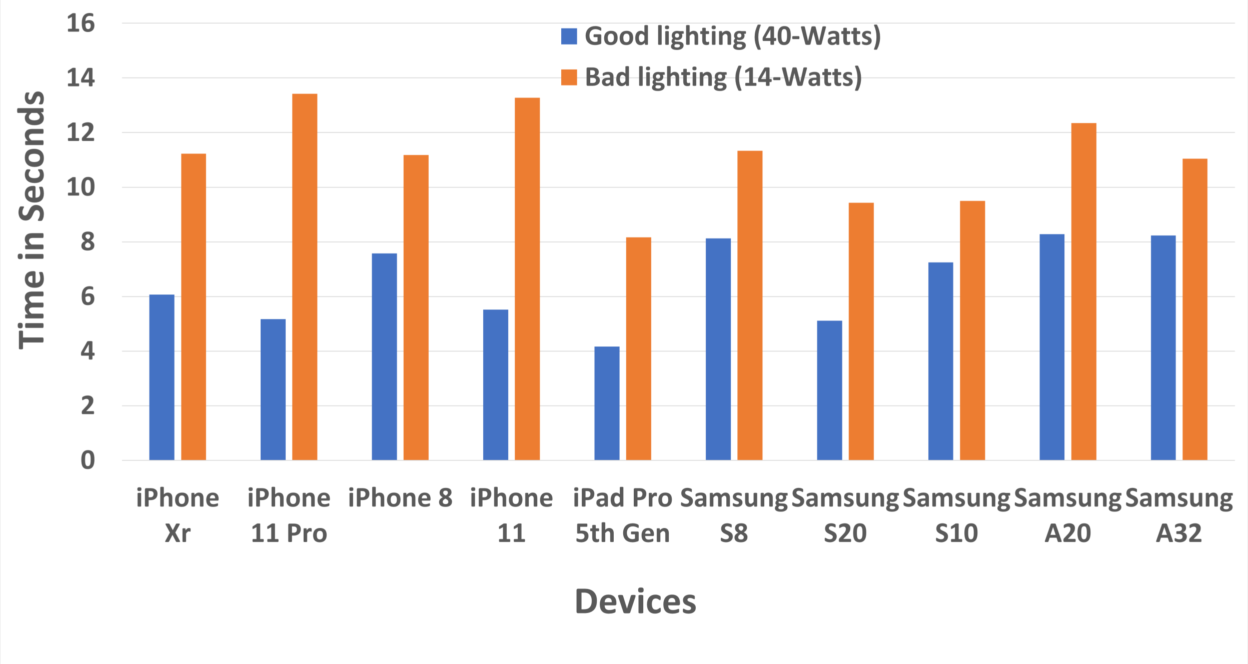


Figure 4.13: Plane detection results under different lighting conditions.

Applying Equation (3.2), the computed average and relative change percentage was compared between the two AR frameworks. Table 4.3 depicts the average time taken for the devices to completely detect planes within the hypothetical crime scene area under 40-Watts and 14-Watts of ambient lighting. In this experiment, the lower the average scan time average the better the result. The following conclusion can be drawn, under 40-Watts of ambient lighting, ARCore devices on average completed the plane detection test in 7.40 seconds. However, ARKit had a marginal lead with an even lower detection average of 6.11 seconds. Under 14-Watts of ambient lighting, ARCore outperformed ARKit by obtaining a plane detection average scan of 11.35 seconds, ARKit in this scenario managed to obtain an average of 11.45 seconds. The following summary can be noted:

- The ARCore framework manages to handle lighting estimation and plane detection better than ARKit under 14-Watts of ambient lighting.
- ARKit, on average, under good ambient lighting (40-Watts) manages to detect horizontal and vertical planes better than ARCore.

It is clear that each AR framework has their strengths and weaknesses. Hence, this should guide future prototyping applications and developments as there may always be trade-offs.

Table 4.3: Plane Detection Summary.

Framework	**40-Watts ambient lighting**	**14-Watts ambient lighting**	**Relative percentage change**
ARCore	7.40s	11.35s	51.08%
ARKit	6.10s	11.45s	90.54%

4.2.3 Resource (CPU and RAM) Utilization

This test criteria evaluated and compared the efficiency of ARKit and ARCore when it comes to random access memory (RAM) and central processing unit (CPU) utilization whilst using the AR Plane detection application. CPU utilization evaluations were conducted on each device after a clean reboot with no background applications running. The mobile device were first checked ten minutes after a reboot for idle CPU loads and then checked again ten minutes after running the developed mobile application for CPU loads. Xcode, an Apple's IDE for developing software for macOS was used to verify this data on ARKit running devices, while CPU profiler, an Android application, which can detect and depict CPU consumption usage was used to verify the ARCore running devices. Figure 4.14 depicts the average CPU usage per device. The lower the CPU utilization during the "running" phase, the more capable the device is. Findings showed that the iPad Pro 5th Gen was the most capable device, while the worst performing device was the Samsung A20. Table 4.4 depicts how the two AR frameworks performed when it came to the CPU utilization test on average.

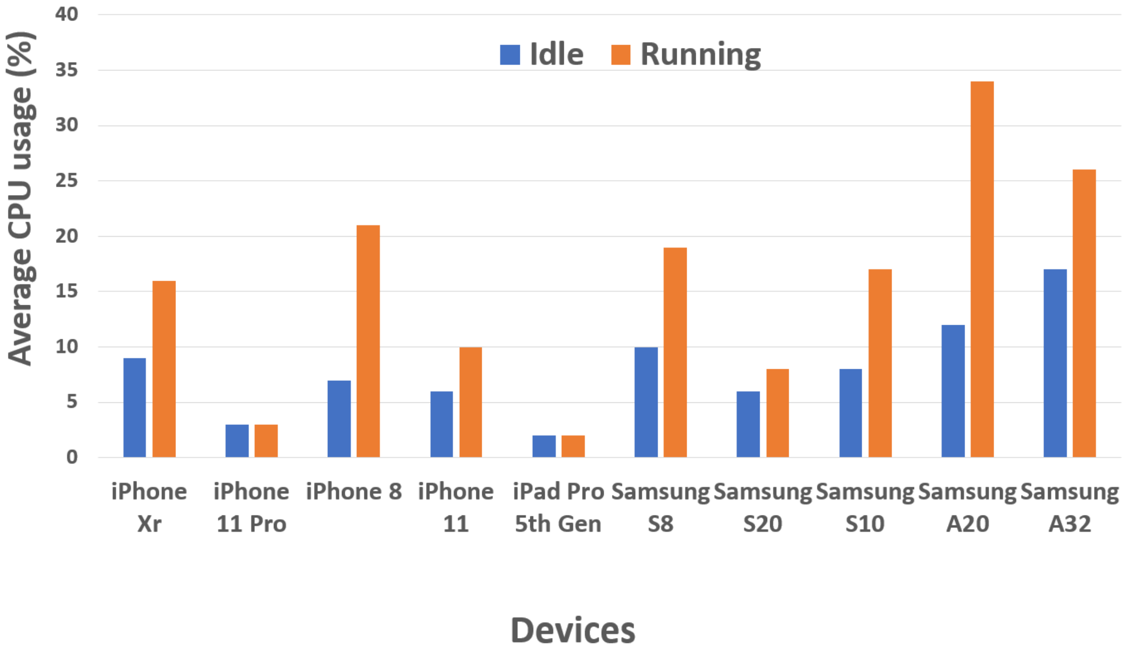


Figure 4.14: Average CPU usage across all devices.

Table 4.4: Relative CPU Average Change.

Framework	Average CPU usage
ARCore	44.92%
ARKit	30.08%

Applying equation (3.2) helped to determine how the devices spanning ARKit and ARCore performed on average. Table 4.4 illustrates a 14.84% lower relative CPU utilization average change for ARKit when compared ARCore. In this test scenario ARKit proved to be the most efficient and optimized AR framework when it comes to AR related applications. A point to also note is that most of the ARKit running devices housed much more powerful processors in comparison to the ARCore devices. However, some lower-end devices from ARCore outperformed ARKit devices.

Figure 4.15 depicts the RAM utilization comparison spanning the ten mobile devices. The notion is that, the lower the RAM utilization the more optimized the device is. For the ARKit framework, the iPhone 8, (running ARKit) performed the worst in this test, while the iPhone 11 Pro (running ARKit) was the most optimised for this application when it comes to RAM management. For ARCore, the Samsung A20 performed the worst, while the best performing device was the Samsung S10.

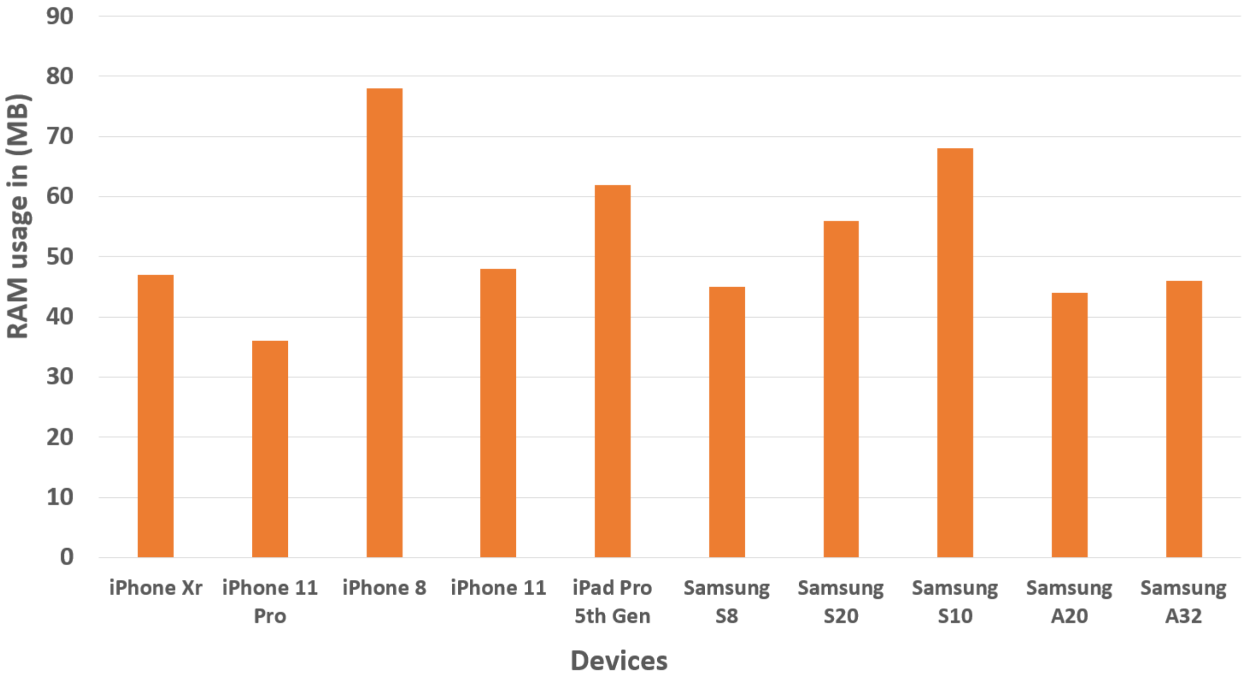


Figure 4.15: RAM usage spanning ten mobile devices.

Table 4.5: RAM utilization comparison between ARCore and ARKit.

Framework	RAM CPU usage
ARCore	51.8MB
ARKit	54.2MB

Table 4.5 presents the average RAM utilization across both AR frameworks, spanning all ten mobile devices. The findings show that ARCore was the most optimised AR framework for this application in comparison to ARKit.

4.3 Empirical Observations on Prototype Application Development

Based on empirical observations on the three major factors earlier explored using the ten mobile devices, the device with the superior performance was used to further develop a prototype application. This device is the iPad Pro 5th Gen, which also housed a LiDAR scanner. The developed prototype application was used with the Vuforia engine to collect and reconstruct 3D crime scene data. The Vuforia engine is a software development kit (SDK) for creating augmented reality applications. The aim of the prototype application is to explore how a mobile AR application could complement the efforts on 3D crime data collection in under-resourced settings.

The following Figures 4.16, 4.17, 4.18, 4.19, 4.20 present the prototype AR mobile application user interface (UI) and navigation process. Figure 4.16 presents the main landing page of the application containing three sub-menu buttons, (i)"AR measure", (ii)"View scenes" and (iii)"AR scenes". Pressing on "AR measure" button opens a sub-menu where a user can conduct AR measurements. Pressing on the "View scenes" button leads to a sub-menu as shown (see Figure 4.17) containing two options to view two sample crime scenes which are; (i) Indoor scene and (ii) Outdoor scenes as shown see (Figure 4.18). This section allows a user to move around the scenes as if they are physically present there, using a navigation wheel and a gyroscope, which offers a spinning and rotation mechanism to get a full $360\circ$ view. Pressing on the "AR scenes" button from the Home screen leads to a sub-menu containing two options as shown (see Figure 4.19). To view the same two aforementioned hypothetical crime scenes however, in this scenario those scenes are augmented and contain AR information overlay of relevant points of interest (POI), Figure 4.20 depicts the indoor and outdoor augmented crime scenes.

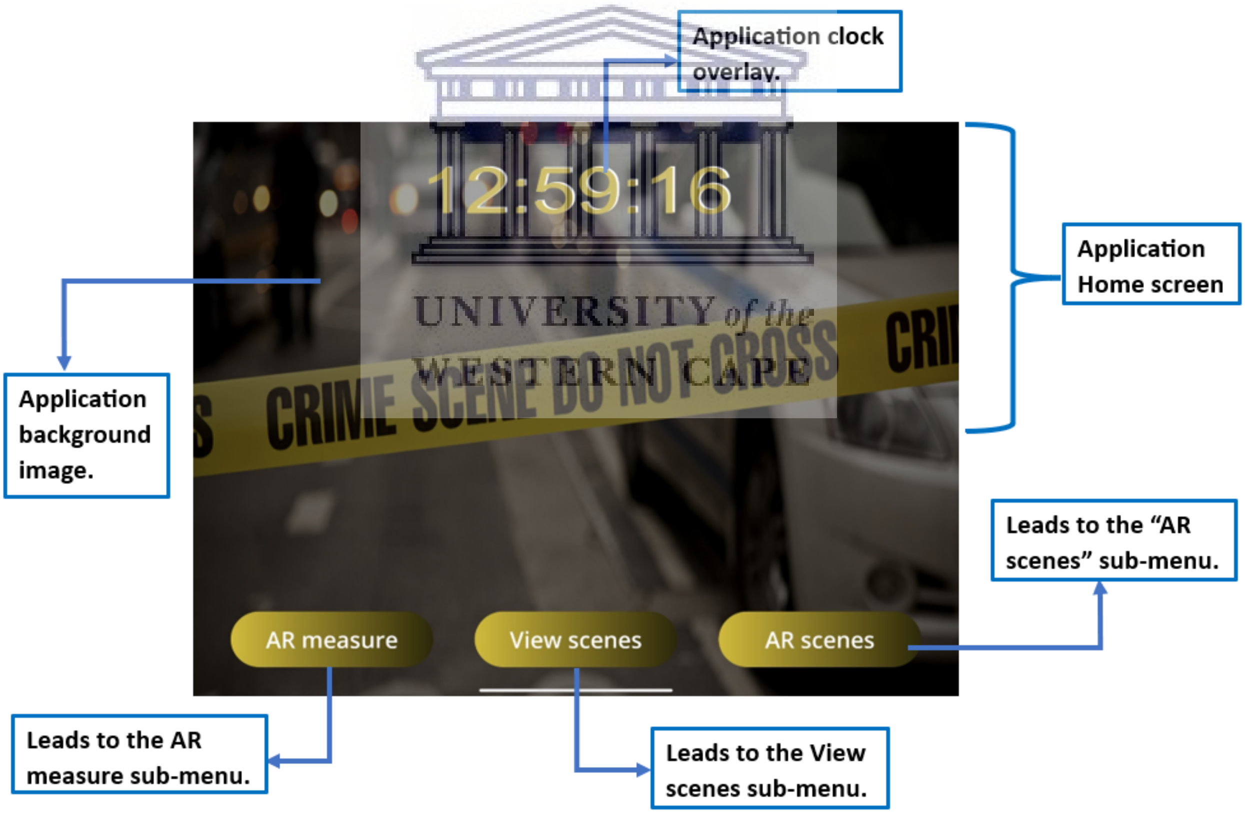


Figure 4.16: Home screen UI.

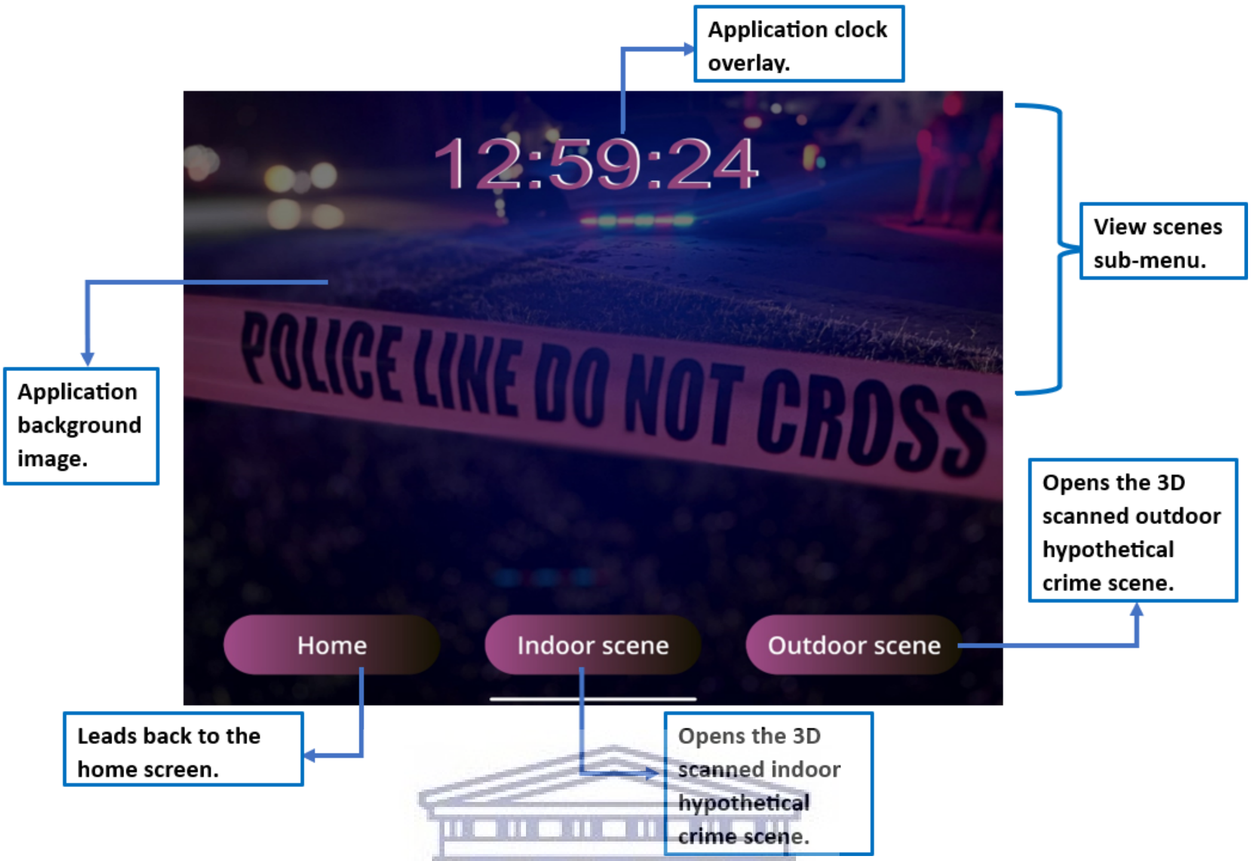


Figure 4.17: View scenes UI.

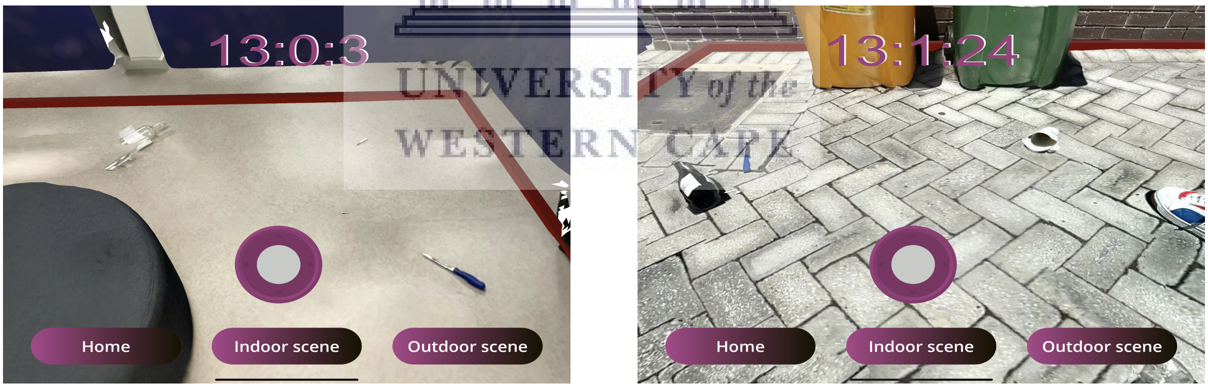
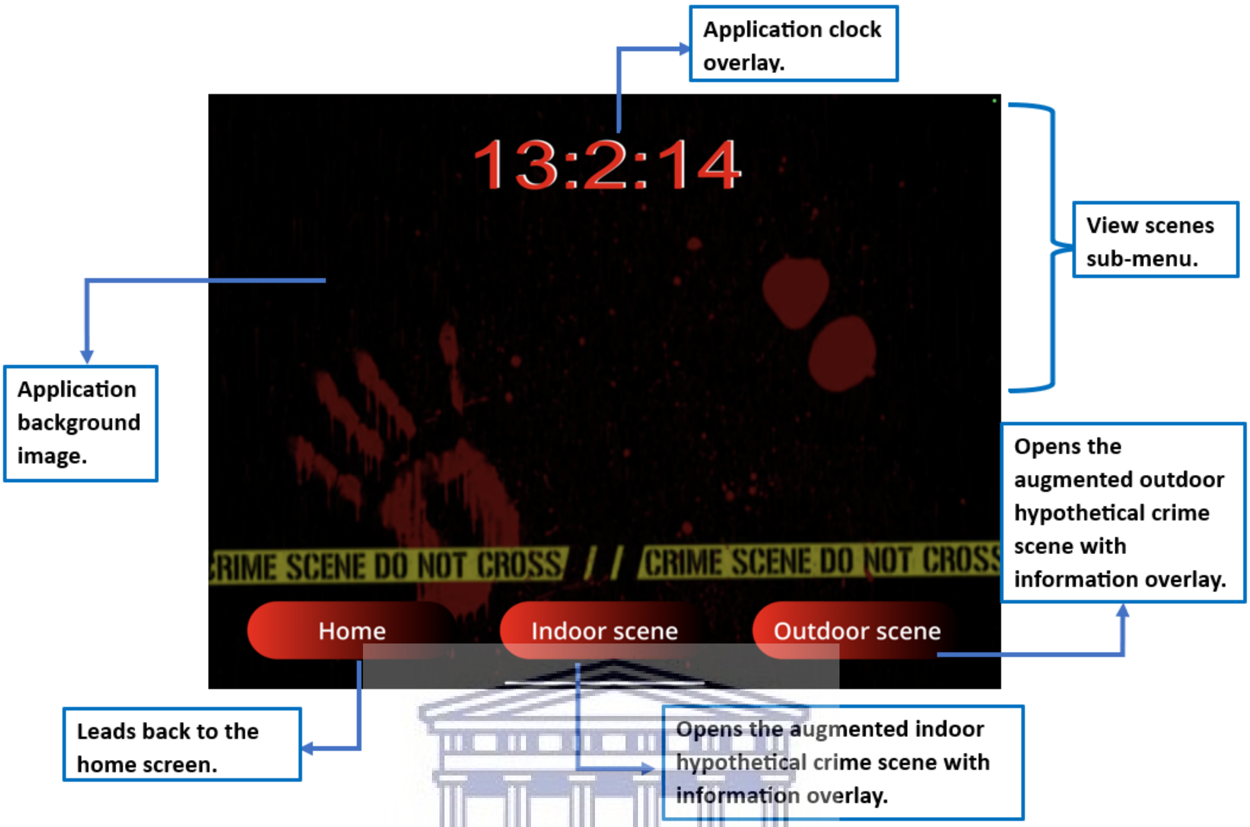


Figure 4.18: View scene sub-menu: Indoor scene (left), Outdoor scene (right).



Application clock overlay.

View scenes sub-menu.

Application background image.

Opens the augmented outdoor hypothetical crime scene with information overlay.

Leads back to the home screen.

Opens the augmented indoor hypothetical crime scene with information overlay.

Figure 4.19: AR scene sub-menu.

Figure 4.20: Indoor (left) and outdoor (right) hypothetical augmented crime scene.

Three major factors were further explored on the final prototype application that was developed using the iPad Pro 5th Gen which are;

- Quality of 3D scanning: using the utilization of a LiDAR scanner
- AR measurements: on the iPad Pro 5th Gen Mobile Device
- 3D scanned scenes: localization re-visitations

4.3.1 Quality of 3D scanning: using the utilization of a LiDAR scanner

For 3D scanning, two 4 meter by 4 meter hypothetical crime scenes were utilized to gather 3D crime scene data. A LiDAR scanner housed on the iPad Pro 5th Gen was utilized to scan and capture this data. Hypothetical crime scene one (1) was conducted indoors and hypothetical crime scene two (2) was conducted outdoors. Figure 4.21 presents the unprocessed 3D data gathered indoors, which can be viewed from multiple angles. Figure 4.22 presents the unprocessed outdoor hypothetical crime scene 3D data. The unprocessed captured data is displayed using the Unity game engine. This software enables users to view 3D scanned data from multiple viewpoints or angles. The 3D crime scene data displayed from the LiDAR scanner was not manipulated to ensure data integrity. A red 4 meter by 4 meter parameter outline was drawn in Unity to depict the scanned area. White artifacts or warping of images from the two hypothetical crime scenes are present, the scanner struggled with those particular areas. This could be due to insufficient lighting for the scanner.

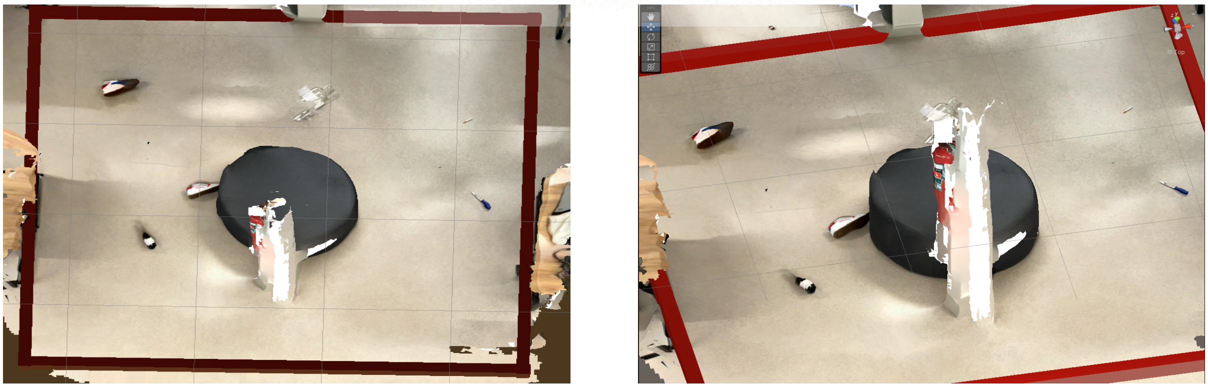


Figure 4.21: Hypothetical indoor crime scene.

Figure 4.22: Hypothetical outdoor crime scene.

Table 4.6 depicts the average time taken to acquire two different crime scenes. In the previous plane detection comparison mentioned above, it was evident that ARKit struggles with light estimation and plane detection under low light in comparison to ARCore. This struggle is evident when we compare the time spent by the ARKit running device (iPad Pro 5th Gen) to completely scan the two crime scenes. For the outdoor hypothetical crime scene Figure 4.22, it took the LiDAR scanner around 1:52 minutes on average to completely scan the entire test area. However, when it came to the indoor crime scene, it took 2:32 minutes on average which is a significant jump. Figure 4.23 and 4.24 show this comparison. Scanned items within the indoor hypothetical crime scene also experienced the most artifacting compared to the outdoor hypothetical crime scene. This could be due to the fact that there was sufficient illumination in the outdoor area compared to the indoor area. Hence, the impact of illumination can not be overlooked when scanning items at a crime scene.

Table 4.6: 4mx4m 3D crime scene scan times.

	Average scan time in minutes	
Device	Indoor	Outdoor
iPad Pro 5th Gen	2:32	1:52

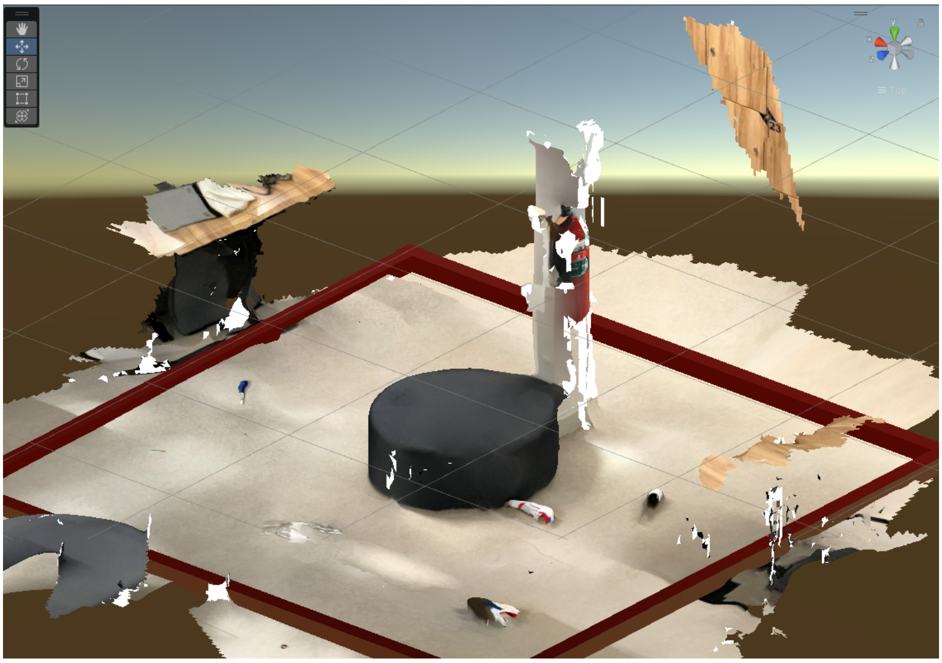


Figure 4.23: Indoor scan artifact.

Figure 4.24: Outdoor scan artifact.

Measurements were conducted to evaluate the LiDAR scanner's degradation point when it comes to accuracy of items within a crime scene, using a tape measure as a control and measuring tools built into the Unity game engine. These measurements were conducted in a similar manner to the AR measurements, however, the lengths of objects and distances between objects were accounted for. In this test case, extrapolated 3D data extracted into Unity and measured showed that the LiDAR scanner used in testing had a deviation error margin of plus or minus (±), 1 cm. This error margin is within an acceptable range when it comes to 3D mapping [105]. However, when it comes to the visual quality, the utilized LiDAR scanner produces visually pleasing detail in well illuminated environments, however, in low illuminated environments the scanner produces a lot of artifacts. The utilized LiDAR scanner appears to struggle a lot with capturing finer details even under adequate illumination. This is to be expected considering the low-cost of the LiDAR scanner and configuration compared to high-end scanners. Unity currently does not support the full capabilities of the iPad's LiDAR scanner as of yet, however, crime scene investigators can still make use of this technology for solving crime. Unity enables investigators to view the localised cluster point cloud data of scanned scenes for further evaluation as seen in Figures 4.25 and 4.26. The localised cluster data is highlighted in orange and is captured the moment an investigator scans a crime scene.

Figure 4.25: Outdoor cluster data.(Best viewed in color mode)

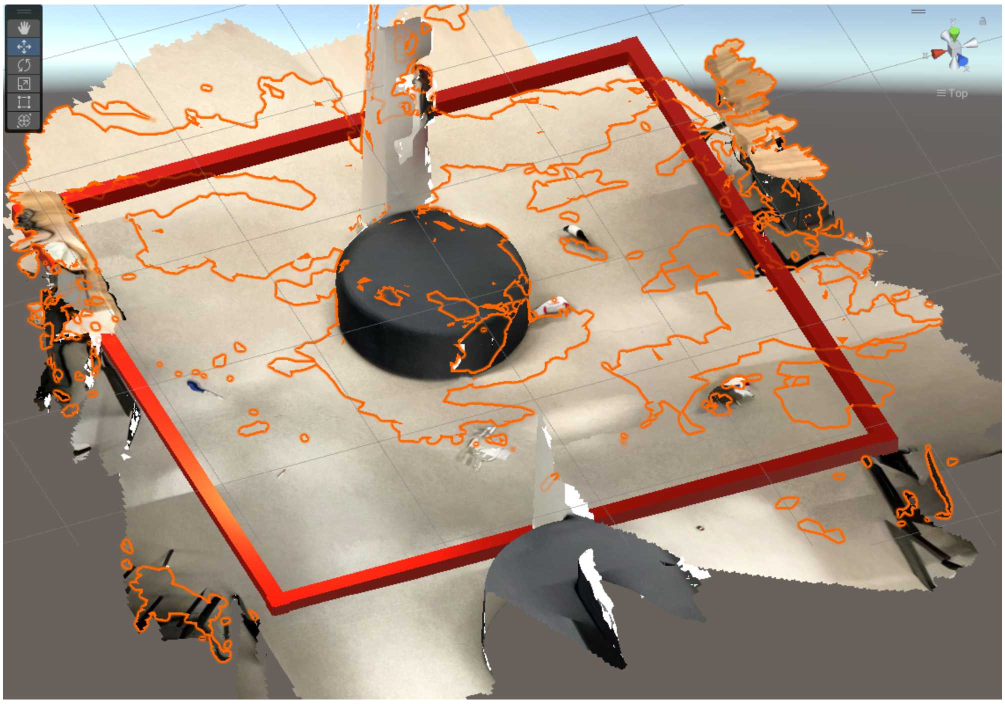


Figure 4.26: Indoor cluster data.(Best viewed in color mode)

4.3.2 AR measurements: on the iPad Pro 5th Gen Mobile Device

Regarding the AR measurements, The initial four (4) test criteria was extended to eight (8) criteria in order to further exploit the use of the iPad Pro 5th Gen device in crime scene data gathering. These criteria are: "10cm", "45cm", "75cm", "100cm", "200cm", "300cm", "400cm" and "500cm". Tables 4.7 and 4.8 depict the raw data findings captured using the iPad Pro 5th Gen running ARKit, based on the 10cm test criteria taken from 1-meter and 2-meters. The tape measure in this test acted as a control, hence the denotation of values being N/A in the first row. Figure 4.27 provides a visual representation of the extrapolated unprocessed data acquired whilst using the iPad Pro 5th Gen. This Figure depicts the comparison between 10cm taken from a distance of 1-meter and 2-meters respectively.

Table 4.7: 10cm AR measurements taken from 1 meter away on the iPad.

Device Name	Result 1 (CM)	Result 2 (CM)	Result 3 (CM)	Result 4 (CM)	Result 5 (CM)	Result 6 (CM)	**Average (CM)**	Best Result (CM)	Worst Result (CM)
Tape measure	N/A	N/A	N/A	N/A	N/A	N/A	**10**	N/A	N/A
iPad Pro 5th Gen	11	10	9	10	9	9	**9.67**	10	11

Table 4.8: 10cm AR measurements taken from 2 meters away on the iPad.

Device Name	Result 1 (CM)	Result 2 (CM)	Result 3 (CM)	Result 4 (CM)	Result 5 (CM)	Result 6 (CM)	**Average (CM)**	Best Result (CM)	Worst Result (CM)
Tape measure	N/A	N/A	N/A	N/A	N/A	N/A	**10**	N/A	N/A
iPad Pro 5th Gen	11	10	9	10	11	9	**10**	10	11

Table 4.9: 10cm computed AR accuracy averages.

Device Name	10cm AR measurement averages		Accuracy stability
Tape measure	1 meter criteria	2 meter criteria	N/A
iPad Pro 5th Gen	9.67cm	10cm	2 meter mark

Table 4.9 provides the calculated average AR measurement per six runs taken from 1-meter and 2-meters. Based on Equation (3.1), the results indicate that the iPad Pro 5th Gen improves in accuracy the further away a user moves from the target being measured when measuring 10cm items in a crime scene. Measurements taken from 1-meter away show a 96.70% accuracy average and measurements taken from 2-meters show a 100% accuracy average measurement for the 10cm criteria. Accuracy averages only provide a single perspective to this study. Accuracy stability is another criteria evaluated. Findings show that when measuring small objects in the ± 10cm range, it is preferable for the investigator to use the 2-meter distance as measurements conducted show a more stable line across all six tests. Figure 4.28 depicts the raw data comparison between 45cm taken from a distance of 1-meter and 2-meters respectively.

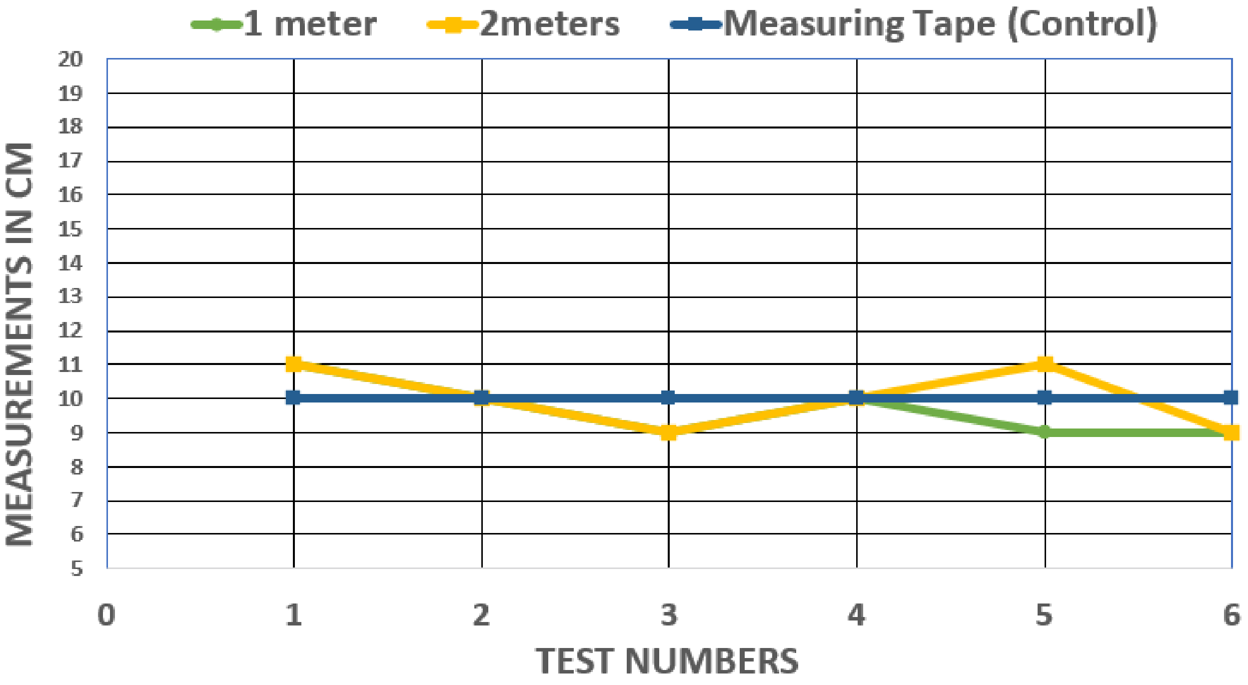


Figure 4.27: 10cm AR Measurements taken from 1 meter and 2 meters away.

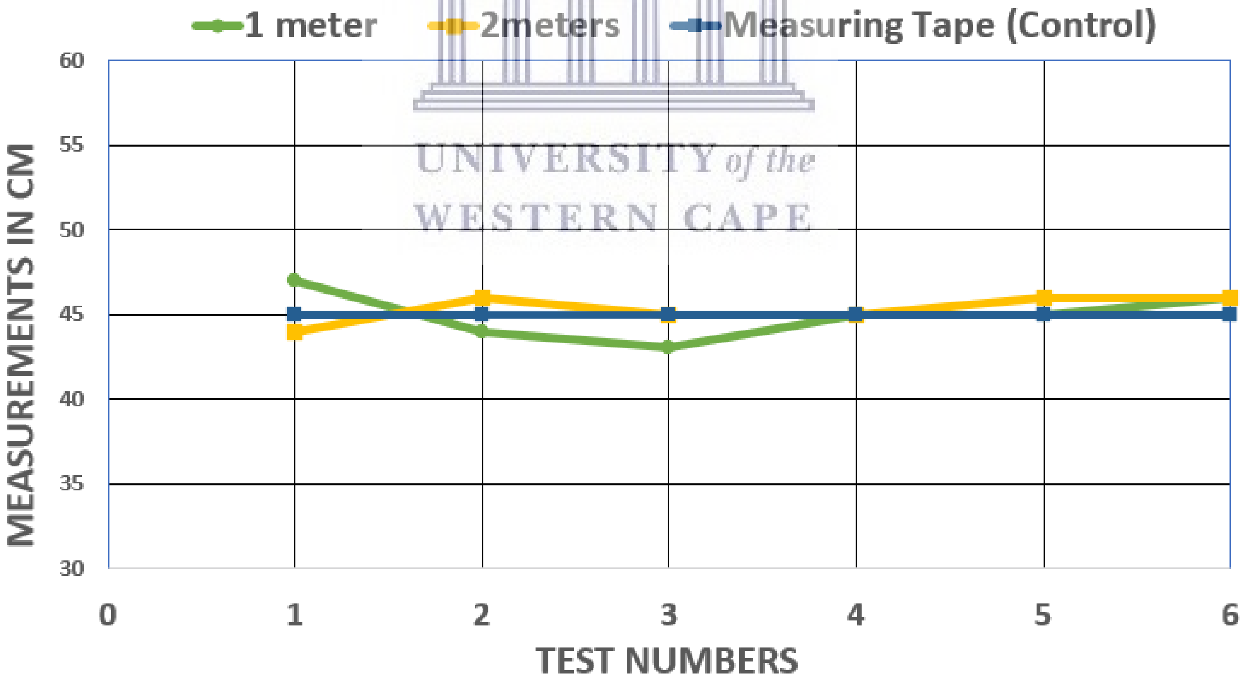


Figure 4.28: 45cm AR Measurements taken from 1 meter and 2 meters away.

Table 4.10: 45cm computed AR accuracy averages.

Device Name	45cm AR measurement averages		Accuracy stability
Tape measure	1 meter criteria	2 meter criteria	N/A
iPad Pro 5th Gen	45cm	45.33cm	2 meter mark

Table 4.10 provides the calculated average AR measurement per six test runs, taken from 1-meter and 2-meters away. Findings indicate that the iPad Pro 5th Gen degrade in accuracy the further away you move from the target being measured with the 45cm mark. Measurements taken from 1-meter indicate a 100% accuracy average measurement, while measurements obtained from 2-meters indicate a 99.27% accuracy average measurement. As far as accuracy stability is concerned, the investigator should use the 2 meter criteria when measuring objects in the 45cm range, as the measurements show a more stable line across all six tests. Figure 4.29 depicts the raw data comparison between 75cm taken from a distance of 1-meter and 2-meters respectively.

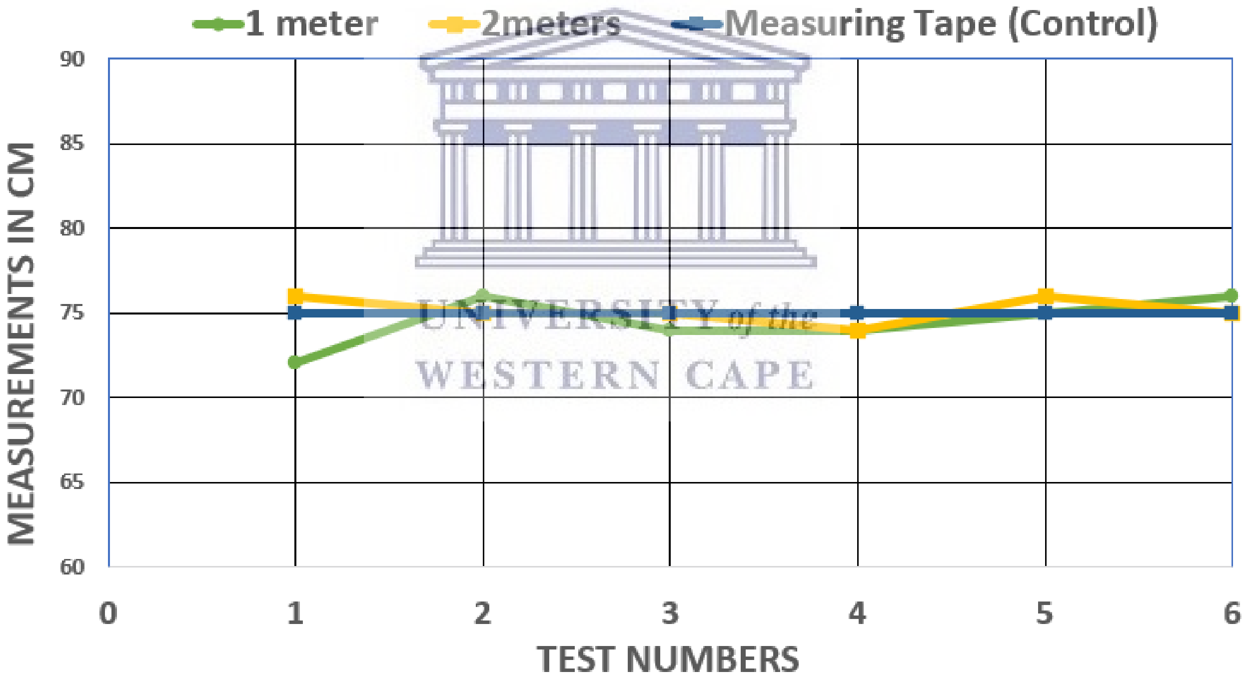


Figure 4.29: 75cm AR Measurements taken from 1 meter away.

Table 4.11: 75cm computed AR accuracy averages.

Device Name	75cm AR measurement averages		Accuracy stability
Tape measure	1 meter criteria	2 meter criteria	N/A
iPad Pro 5th Gen	74.5cm	75.17cm	2 meter mark

Table 4.11 illustrates that the iPad Pro 5th Gen improves accuracy the further away you move from the target being measured, in the case of items that are measuring 75cm apart. Measurements taken from 1-meter away indicate a 99.33% accuracy average and measurements taken from 2-meters indicate a 99.77% accuracy average measurement. According to the results of the experiments conducted, when measuring objects in the ±75cm range, it is preferable to use the 2 meter criteria, since all six tests show a more stable trend line. Figure 4.30 depicts the raw data comparison between 100cm taken from a distance of 1-meter and 2-meters respectively.

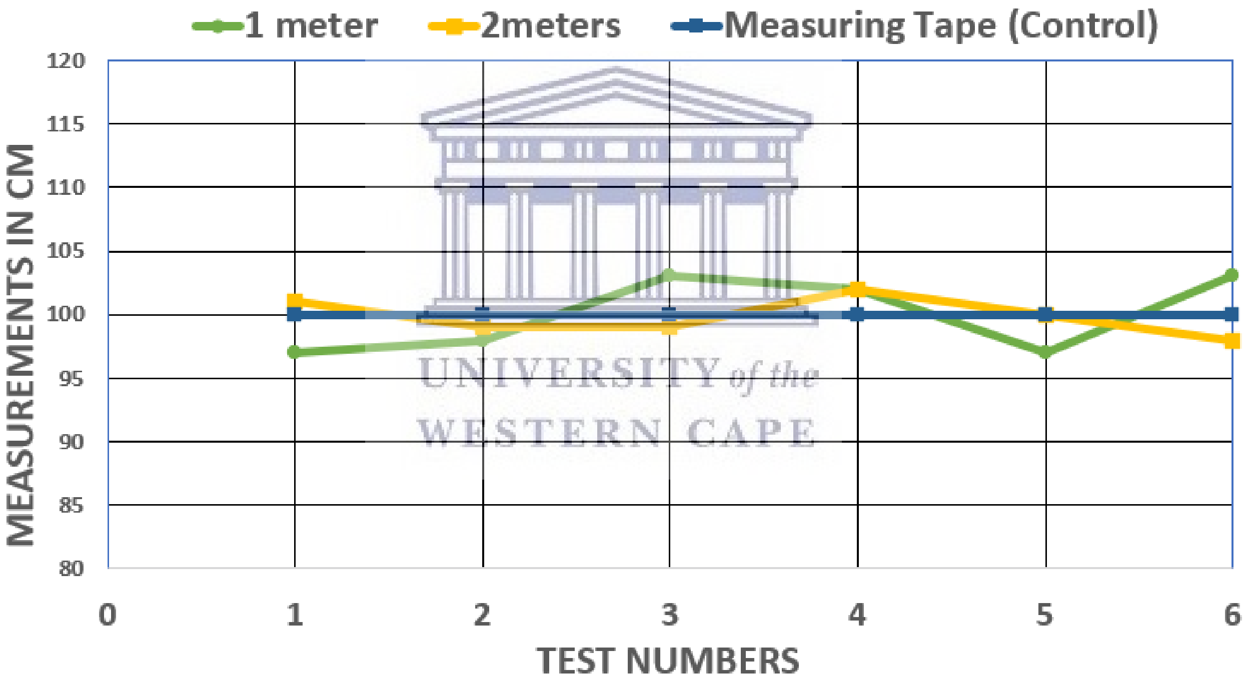


Figure 4.30: 100cm AR Measurements taken from 1 meter and 2 meters away.

Table 4.12: 100cm computed AR accuracy averages.

Device Name	100cm AR measurement averages		Accuracy stability
Tape measure	1 meter criteria	2 meter criteria	N/A
iPad Pro 5th Gen	100cm	99.83cm	2 meter mark

Table 4.12 illustrates that the iPad Pro 5th Gen degrades in accuracy the further away you move from the target being measured, with respect to measuring items that are 100cm apart. Measurements taken from 1-meter away show a 100% accuracy average and measurements taken from 2-meters show a 99.83% accuracy average. When measuring objects in the 100cm range, the investigator should use the 2 meter criteria as the results show a more stable line across all six measurements. Figure 4.31 depicts the raw data comparison between 200cm taken from a distance of 1-meter and 2-meters respectively.

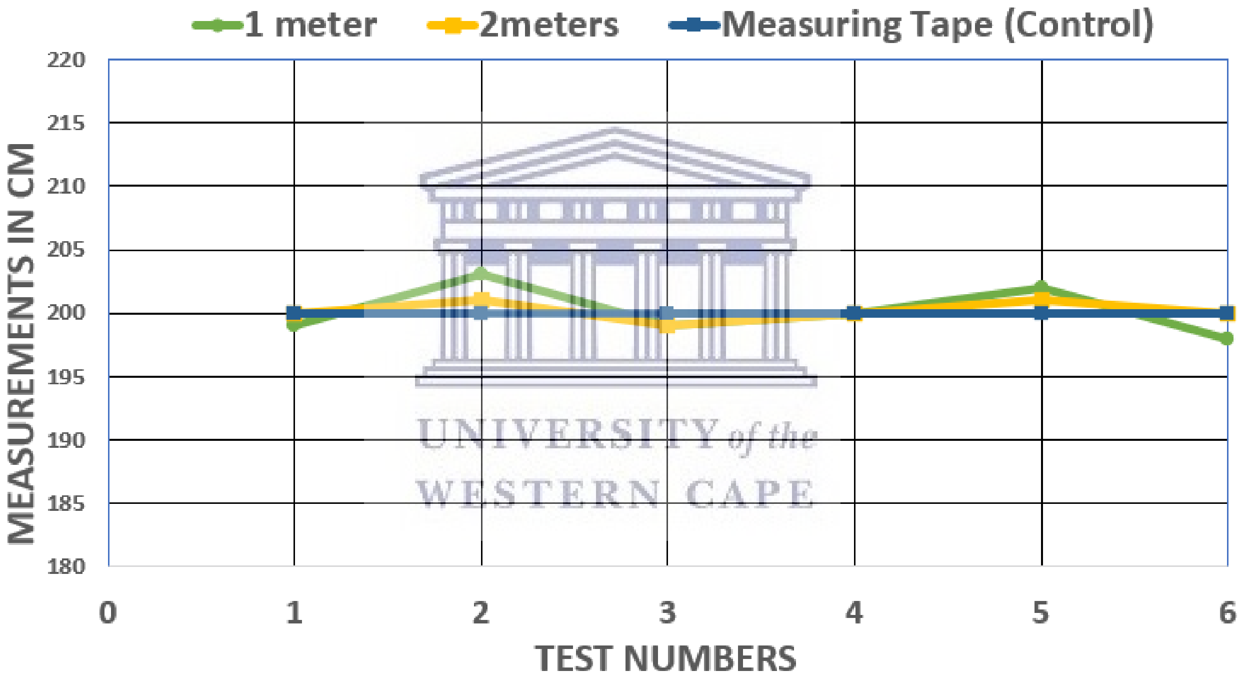


Figure 4.31: 200cm AR Measurements taken from 1 meter and 2 meters away.

Table 4.13: 200cm computed AR accuracy averages.

Device Name	200cm AR measurement averages		Accuracy stability
Tape measure	1 meter criteria	2 meter criteria	N/A
iPad Pro 5th Gen	200.17cm	200.17cm	2 meter mark

Table 4.13 illustrates that the iPad Pro 5th Gen attained the same average accuracy when measuring 200cm items taken from 1-meter and 2-meters respectively. Measurements taken from 1-meter away indicate a 99.99% accuracy average while, measurements taken from 2-meters indicate a 99.99% accuracy average measurement. For the accuracy stability, findings show that when measuring objects in the ± 200cm range, it is preferable for the investigator to use the 2 meter criteria as measurements conducted show a more stable line across all six tests. Figure 4.32 depicts the raw data comparison between 300cm obtained from a distance of 1-meter and 2-meters respectively.

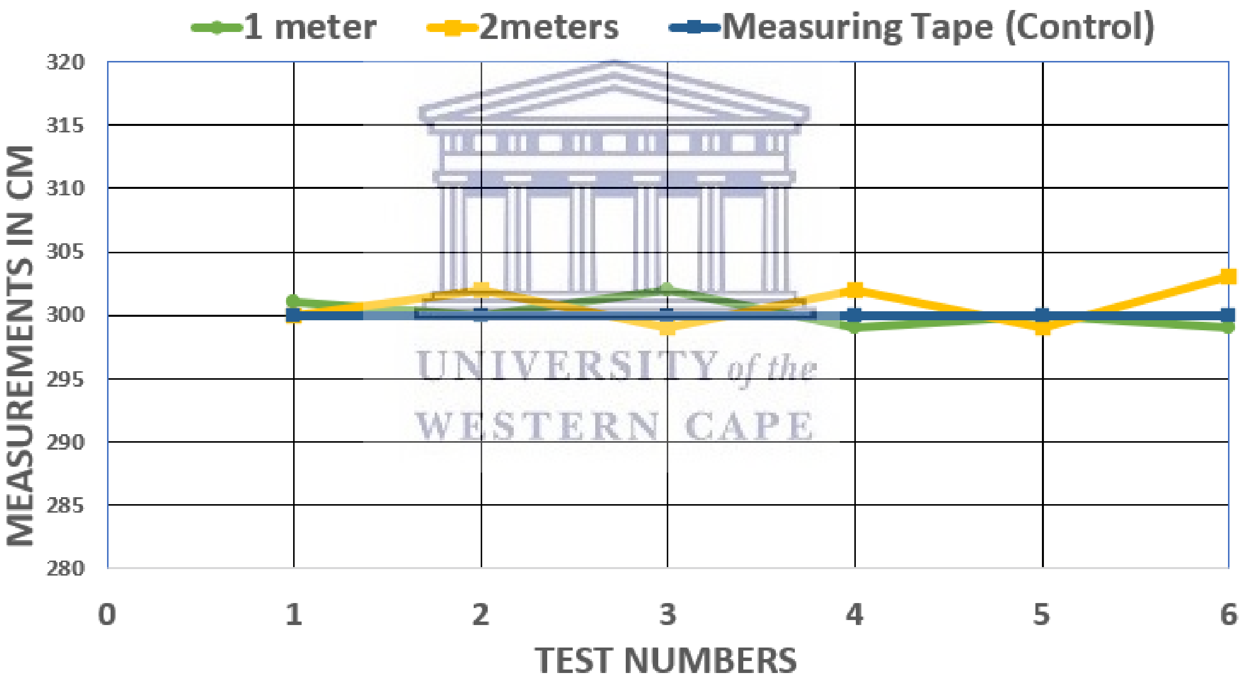


Figure 4.32: 300cm AR Measurements taken from 1 meter and 2 meters away.

Table 4.14: 300cm computed AR accuracy averages.

Device Name	300cm AR measurement averages		Accuracy stability
Tape measure	1 meter criteria	2 meter criteria	N/A
iPad Pro 5th Gen	300.17cm	300.83cm	1 meter mark

Table 4.14 illustrates that the iPad Pro 5th Gen improved accuracy when moving from 1-meter to 2-meter. Measurements taken from 1-meter away indicate a 99.44% accuracy average and measurements taken from 2-meters show an average measurement accuracy of 99.72%. For accuracy stability, findings show that when measuring objects in the ± 300cm range, it is preferable for the investigator to use the 1 meter criteria as measurements conducted indicate a more stable line across all six tests. Figure 4.33 depicts the raw data comparison between 400cm taken from a distance of 1-meter and 2-meters respectively.

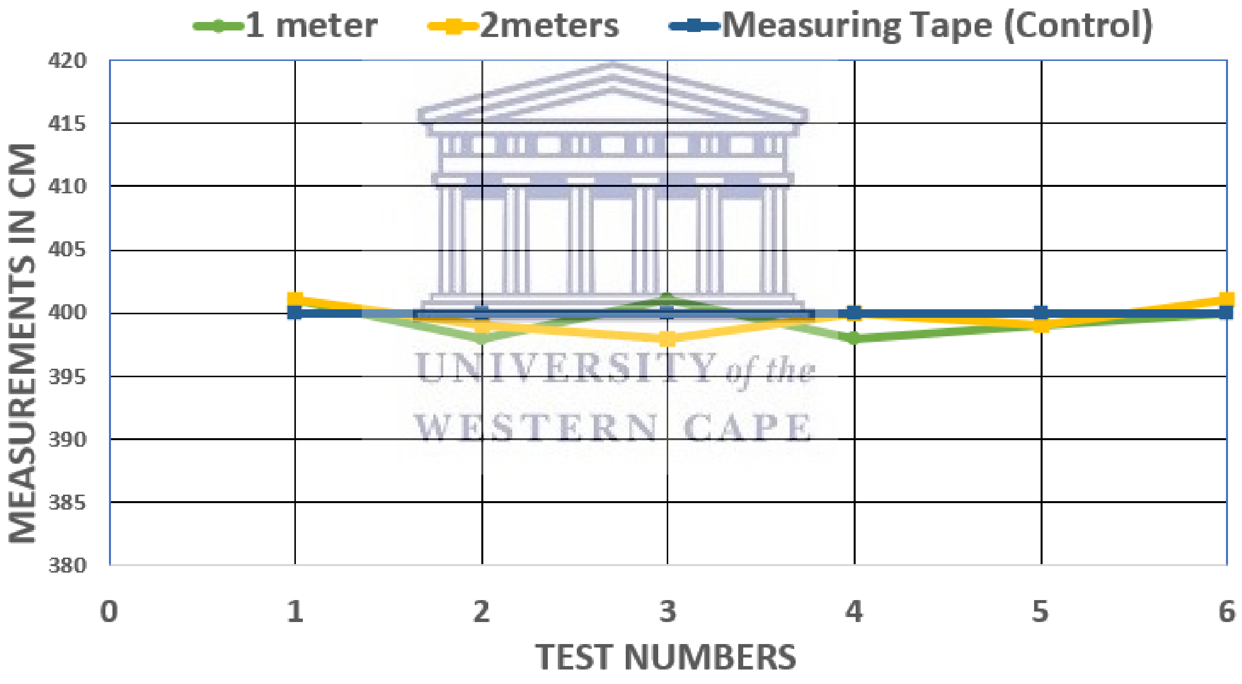


Figure 4.33: 400cm AR Measurements taken from 1 meter and 2 meters away.

Table 4.15: 400cm computed AR accuracy averages.

Device Name	400cm AR measurement averages		Accuracy stability
Tape measure	1 meter criteria	2 meter criteria	N/A
iPad Pro 5th Gen	399.50cm	399.67cm	2 meter mark

Table 4.15 illustrates that the iPad Pro 5th Gen improved average accuracy when moving from 1-meter to 2-meter. Measurements taken from 1-meter away indicate a 99.88% accuracy average and measurements taken from 2-meters indicate a 99.91% accuracy average measurement. Findings indicate that when measuring objects within the ± 400cm range, it is more favorable for the investigator to use the 2 meter criteria, since all six measurements indicate a more stable line. Figure 4.34 depicts the raw data comparison between 500cm taken from a distance of 1-meter and 2-meters respectively.

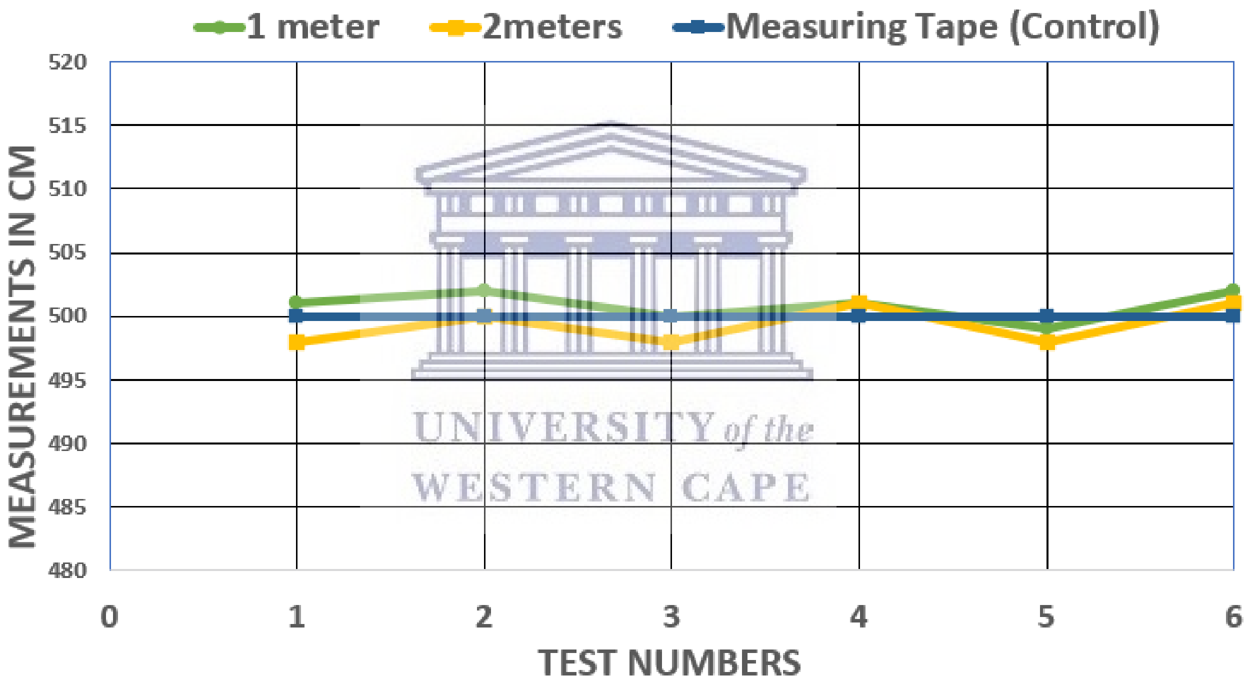


Figure 4.34: 500cm AR Measurements taken from 1 meter and 2 meters away.

Table 4.16: 500cm computed AR accuracy averages.

Device Name	500cm AR measurement averages		Accuracy stability
Tape measure	1 meter criteria	2 meter criteria	N/A
iPad Pro 5th Gen	500.83cm	499.33cm	1 meter mark

Table 4.16 illustrates that the iPad Pro 5th Gen improved accuracy when moving from 1-meter to 2-meter. Measurements taken from 1-meter away indicate a 99.83% accuracy average and measurements taken from 2-meters indicte a 99.87% accuracy average measurement. Findings show that when measuring objects within the ± 500cm range, using the 1 meter criteria would provide a more stable line across all six measurements. Table 4.17 provides a summary of the stability trend-line in regards to the eight distance criteria used in testing with the iPad Pro 5th. A reading of "Stable" refers to the preferable measurement distance to conduct AR measurements, a reading of "Not stable" refers to a non-preferable measurement distance.

Table 4.17: AR measurement trend-line summary conducted with the iPad Pro 5th Gen.

Measure criteria	1-meter	2-meters
10cm	Not stable	Stable
45cm	Not stable	Stable
75cm	Not stable	Stable
100cm	Not stable	Stable
200cm	Not stable	Stable
300cm	Stable	Not stable
400cm	Not stable	Stable
500cm	Stable	Not stable

4.3.3 3D scanned scenes: localization re-visitations

This last section evaluates the localization of already scanned crime scenes once they have been cleared up. Cleared up referring to after some time has passed (weeks, months or even years) after a crime has been committed) This feature, 3D scanned scenes, in the developed prototype application allows an investigator to physically (virtually) revisit an already cleared crime scene. AR information overlay plays a crucial role in this section. It highlights the relevant POI present on the day a crime scene was scanned. Figure 4.35 depicts the indoor hypothetical crime scene used in testing (left) and an augmented version of the same crime scene (right), for example, (two months after it has been cleared). Figure 4.36 depicts the outdoor hypothetical crime scene (left) and the augmented crime scene area (right) two months after it has been cleared viewed at a different angle.

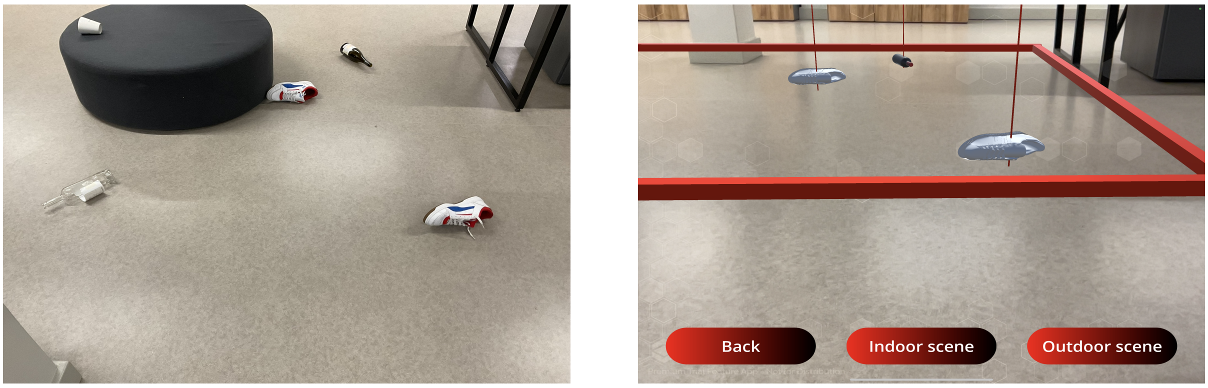


Figure 4.35: Non augmented and augmented hypothetical indoor crime scene revisit.

Figure 4.35 shows that even after a period of time has passed, and items have been removed such as the circular grey couch shown in the (left), localization of relevant POI can still be overlayed for crime scene investigators. The same can be said about Figure 4.36, localized 3D data can still be revisited in future and relevant POI will appear as shown on the (right) image of the Figure.

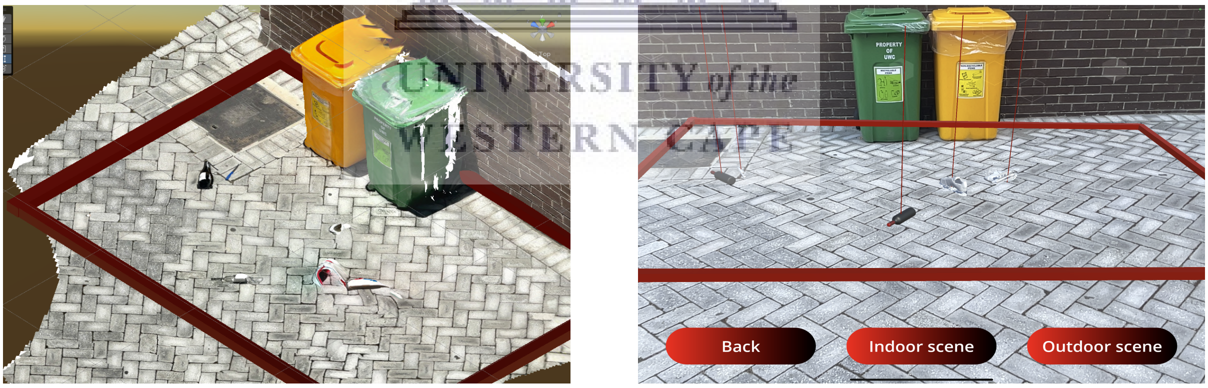


Figure 4.36: Non augmented and augmented hypothetical outdoor crime scene revisit.

Findings suggest that hypothetical indoor and outdoor crime scene areas were accurately and reliably localized based on the stored POIs set on the first day of scanning. This shows that this proposed low-cost solution would be very applicable for crime scene investigation revisits even after the scene has been cleared.

4.4 Chapter Summary

This chapter presents quantitative and qualitative experimental results. The results revealed the potential usefulness of the iPad Pro 5th Gen's LiDAR scanner for 3D measurements and crime scene data collection. This presents an alternative to complement the investigation goals of crime investigators on 3D crime data collection, particularly in low-resource settings where high-end technologies are not available. The evaluation of the two prominent mobile AR frameworks, ARKit and ARCore illustrated that even though these frameworks aim to achieve similar goals, the level of accuracy may not necessarily be the same. This was evident in the factors investigated such as AR measurement of items at a crime scene, plane detection and resource (CPU/RAM) utilization. Findings indicated that AR measurements are better done using the ARKit framework, given the high level of precision and accuracy associated with crime data collection and investigation. The ARKit framework achieved an average accuracy of 97.52% while ARCore attained 89.42%. Results further suggest that it is preferable to conduct AR measurements from the 2-meter mark of an observer's point of reference as this gave relatively stable results. It is also important to use ARKit under adequate ambient lighting for proper plane detection as this impacts on the quality of 3D mapping and plane detection, whereas ARCore relatively excelled under low ambient lighting conditions.

Chapter 5

CONCLUSION, RECOMMENDATION AND FUTURE WORK

The proposition of this research was that exploring a potentially low cost solution could offer a way to assist public safety and crime scene investigators in low-resource settings. Furthermore, past literature suggests that there is a paucity of research work on the area of 3D crime scene reconstruction from developing countries. To address this proposition, three research questions were considered:

- Firstly, What are the traditional methods of crime scene data capturing? How have these methods evolved and been used by investigators to capture and reconstruct crime scene? What are their limitations?
- Secondly, How can the development of a mobile application with the integration of immersive technology alongside a 3D scanner supplement accuracy issues posed by traditional methods of crime scene data gathering through 3D crime scene reconstructions?
- Thirdly, What level of confidence can be achieved with the developed mobile application, particularly using the two major mobile AR frameworks (i.e., ARKit and ARCore) of immersive technologies?

This chapter summarises and concludes this research. The discussion in this chapter elucidates how the empirical analysis and findings addressed the research questions. Thereafter, suggested recommendation and opportunities for future research is documented.

5.1 Research Summary and Conclusion

While this research considered a crime scene as an application scenario, it is important to note that the idea in this research can be extended to other domains that require some form of 3D scene data collection and reconstruction. The motivation for considering the crime domain is the incessant challenges faced by crime investigators in low-resources settings, such as Africa and paucity of research on the application of immersive technology in the domain.

5.2 Synthesis of Empirical Findings

5.2.1 What are the traditional methods of crime scene data capturing? How have these methods evolved and been used by investigators to capture and reconstruct crime scene? What are their limitations?

Traditional methods of crime scene data collection include digital media (photography and videography), hand sketches, manual measurements and paper documentation. These methods have evolved in a variety of ways, from the integration of photogrammetry, 360 panoramic imaging techniques and immersive technologies such as augmented reality (AR)/ virtual reality (VR), to mention a few. Investigators have used traditional methods in the following manner. Digital media has been used to capture images or videos pertaining to crime scenes. Hand sketches have been used to quickly capture data within a crime scene e.g. a description of the perpetrator's face through the use of paper and pen. Manual measurements have been used to measure distances between items found at a crime scene. These are normally conducted with a tape measure or a laser finder. Paper documentation is normally used to quickly jot down relevant points of interest (POI) at a crime scene. The limitations of these traditional methods are that they capture data in 2D format and are inefficient or inaccurate at reproducing 3D visualizations of crime scene investigations. Digital media at times can suffer from what is referred to as image distortion caused by the camera post-processing. Furthermore, the quality and authenticity (accuracy) of the data collected would be highly dependent on the skills and strengths of the investigator. For example, fatigue and stress could greatly impact on the quality and accuracy of information collected by an investigator.

5.2.2 How can the development of a mobile application with the integration of immersive technologies alongside a 3D scanner supplement accuracy issues posed by traditional methods of crime scene data gathering through 3D crime scene reconstructions?

To address this research question, an experiment was first conducted on the two (2) major AR frameworks (ARKit and ARCore) with ten mobile devices based on three (3) major factors, (i) AR measurements, (ii) Plane detection and (iii) resource (CPU/RAM) utilization. Ten mobile devices (five for ARCore and five for ARKit) were utilised. The ARCore running device are the Samsung S8, Samsung S10, Samsung S20, Samsung A20 and Samsung A32. While the ARKit running devices are the iPhone Xr, iPhone 11 pro, iPhone 8, iPhone 11 and the iPad Pro 5th Gen. The choice of the distance criteria used for the AR measurements were guided by experts in this domain of interest. The reason these ten devices were utilised is because they offer the greatest variation in terms of age (i.e., roll-out history) and AR framework support. Age variation refers to the comparison of older devices e.g. Samsung S8 compared to S20. This variation was assessed to determine whether there was a significant difference in terms of performance regarding newer technology optimization and older devices. AR framework support refers to the oldest devices supported within the latest AR frameworks used in testing. Empirical observations from the experiment suggests that the iPad Pro 5th Gen mobile device is more promising. Hence, this further exploration was used to develop a prototype AR mobile application.

Based on the tested crime scenes with a 4 meter by 4 meter parameter ranging from 10cm to 500cm, the developed AR mobile application showed a deviation error margin of within ±1 cm. The integration of immersive technologies (AR) alongside a LiDAR scanner has proven to be very promising when it comes to 3D reconstructions and measurements, very affordable for low-resource areas and a viable solution for crime scene investigators. This solution could be a viable addition to traditional crime scene reconstruction methods used by forensic investigators, if adopted. Furthermore, the exploration is that a potentially low-cost solution could alleviate some of the current challenges faced by crime investigators in low-resource settings, such as display limitation, Low precision, image distortion, and human error.

5.2.3 What level of confidence can be achieved with the developed mobile application, particularly using the two major mobile AR frameworks of immersive technologies?

The level of confidence that can be achieved with the developed mobile application is quite significant in the sense that the use of ARKit for AR measurements recorded an average accuracy of 97.52% while ARCore recorded an average accuracy of 89.42% based on the test criteria. For horizontal and vertical plane detections both AR frameworks mapped out the designated test area. However, ARKit was superior to ARCore under favourable ambient lighting of 40-Watts, however, ARCore was superior to ARKit under limited ambient lighting of 14-Watts. In terms of resource (CPU/RAM) utilization, ARKit is the most efficient AR framework when it comes to CPU processing.

It is important to note that there is no bias in the experiment as the AR frameworks are not interchangeable between the different operating systems. These frameworks rely on different operating systems because their vendors do not cater for cross-platform functionality. Apple specifically makes ARKit for only Apple devices and Google makes ARCore for only Android running devices. The researcher has no control over this choice of frameworks from the vendors. Furthermore, the frameworks were each tested with five different devices, to further eliminate bias, this test was done on a multitude of different hardware configurations and operating system configurations from both Apple and Google. For example, the Samsung A20 was running Android 11 whilst the Samsung S20 ran Android 12, which are two distinct operating system versions. On the Apple side, there was iPad OS 15 whilst the 11pro was on iOS 16. It is worth nothing that both frameworks have their strengths, and this is expected to improve as vendors continually seek to upgrade their solutions.

5.3 Recommendation and Limitations of Research

5.3.1 Recommendation

This research has led to a variety of recommendations ranging from (i) which AR framework is suitable for AR measurements to (ii) light estimation and plane detection. Regarding AR measurements it would be highly advisable for developers or users within the forensic science domain to explore ARKit when it comes to accuracy and reliability in AR measurements. Measurements between items at a crime scene ranging between 10cm and 500cm, should be taken at 2-meters away from the target being measured. When it comes to light estimation and detection for horizontal and vertical planes, ARKit is the most preferable AR framework, based on the devices and parameters considered in this research. This is due to the fact that this AR framework captures and maps out planes much quicker than ARCore based on the parameters that are set out within the experiment conducted in this research.

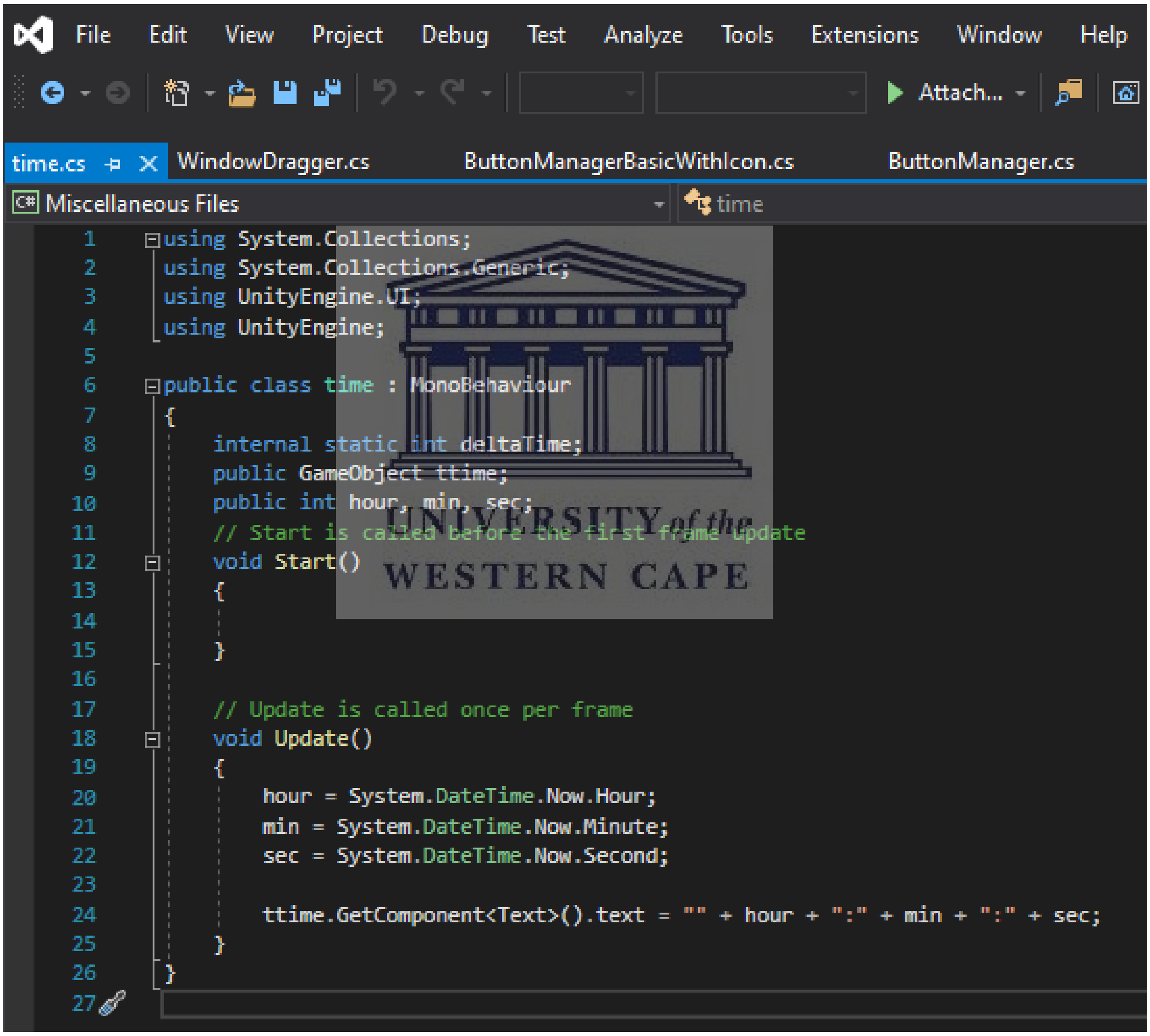
5.3.2 Limitations

By integrating immersive technologies and utilizing a cost-effective LiDAR scanner, the research showed some limitations. Limitations such as poor detail levels of 3D scanned data $\geq$ 10 cm. This is expected due to the low price and features of the device used in testing (iPad Pro 5th Gen) compared to other high-end options. The use of a LiDAR scanner on clear or transparent objects such as glass or windows causes an artifacting issue resulting in inaccurate scans. The use of the aforementioned version of the Mac Mini desktop was a problematic issue for research as this device led to bottlenecking when developing the mobile AR prototype application. Furthermore, the developed mobile application could not be tested with crime scene investigators due to the constraints of bureacracy and research timeline.

5.4 Opportunities for Future Research

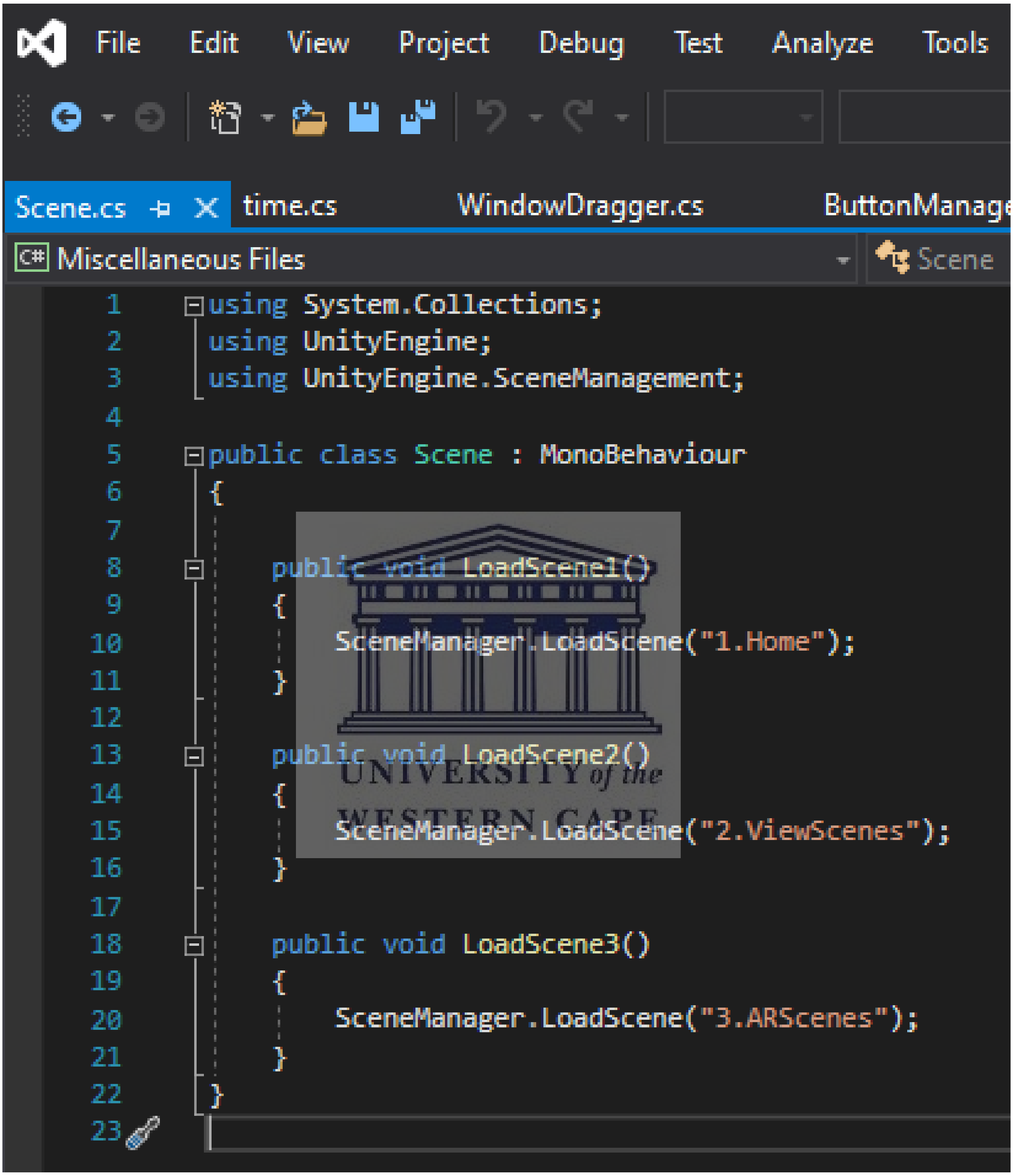
This research has explored a low-cost solution for low-resource areas, especially in Africa, by developing an AR mobile application using an iPad 5th Gen's LiDAR scanner and immersive technologies. However, there is great potential to extend the current research for crime scene investigators and forensic science for future adoption. Future research could consider the solubility and storage management of crime scene data and the use of block chain-based techniques for secure file sharing amongst several investigators. Furthermore, the current solution could be tested at an actual crime scene and the results compared with measurements and 3D reconstruction obtained from a high-end solution. The solution presented in this research could also be extended to other relevant domains that require some 3D measurements and plane detection.

Appendix A



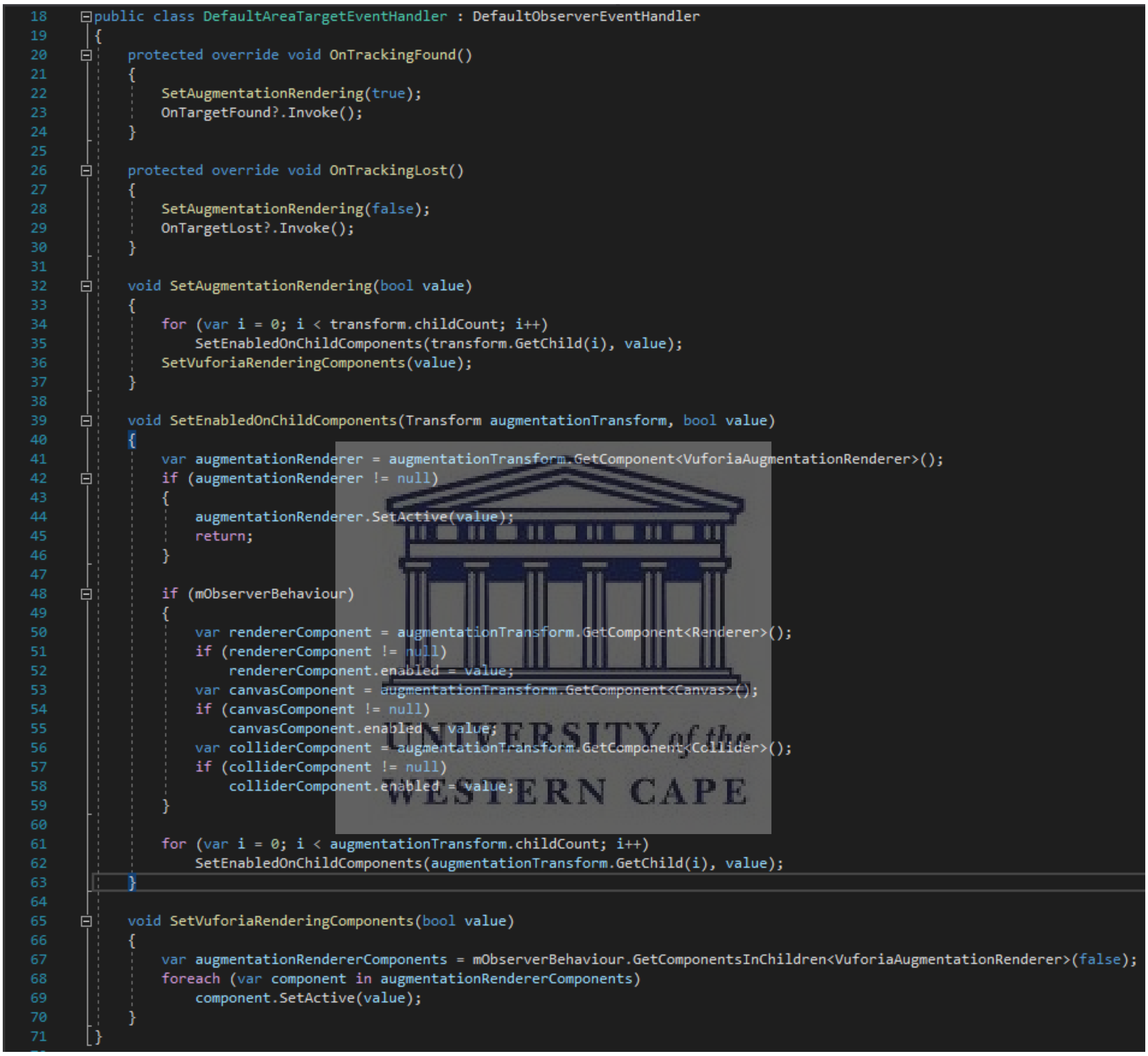
```
using System.Collections;
using System.Collections.Generic;
using UnityEngine.UI;
using UnityEngine;

public class time : MonoBehaviour
{
    internal static int deltaTime;
    public GameObject ttime;
    public int hour, min, sec;
    // Start is called before the first frame update
    void Start()
    {

    }

    // Update is called once per frame
    void Update()
    {
        hour = System.DateTime.Now.Hour;
        min = System.DateTime.Now.Minute;
        sec = System.DateTime.Now.Second;

        ttime.GetComponent<Text>().text = "" + hour + ":" + min + ":" + sec;
    }
}
```

Figure A.1: C# time script used in menu UI.



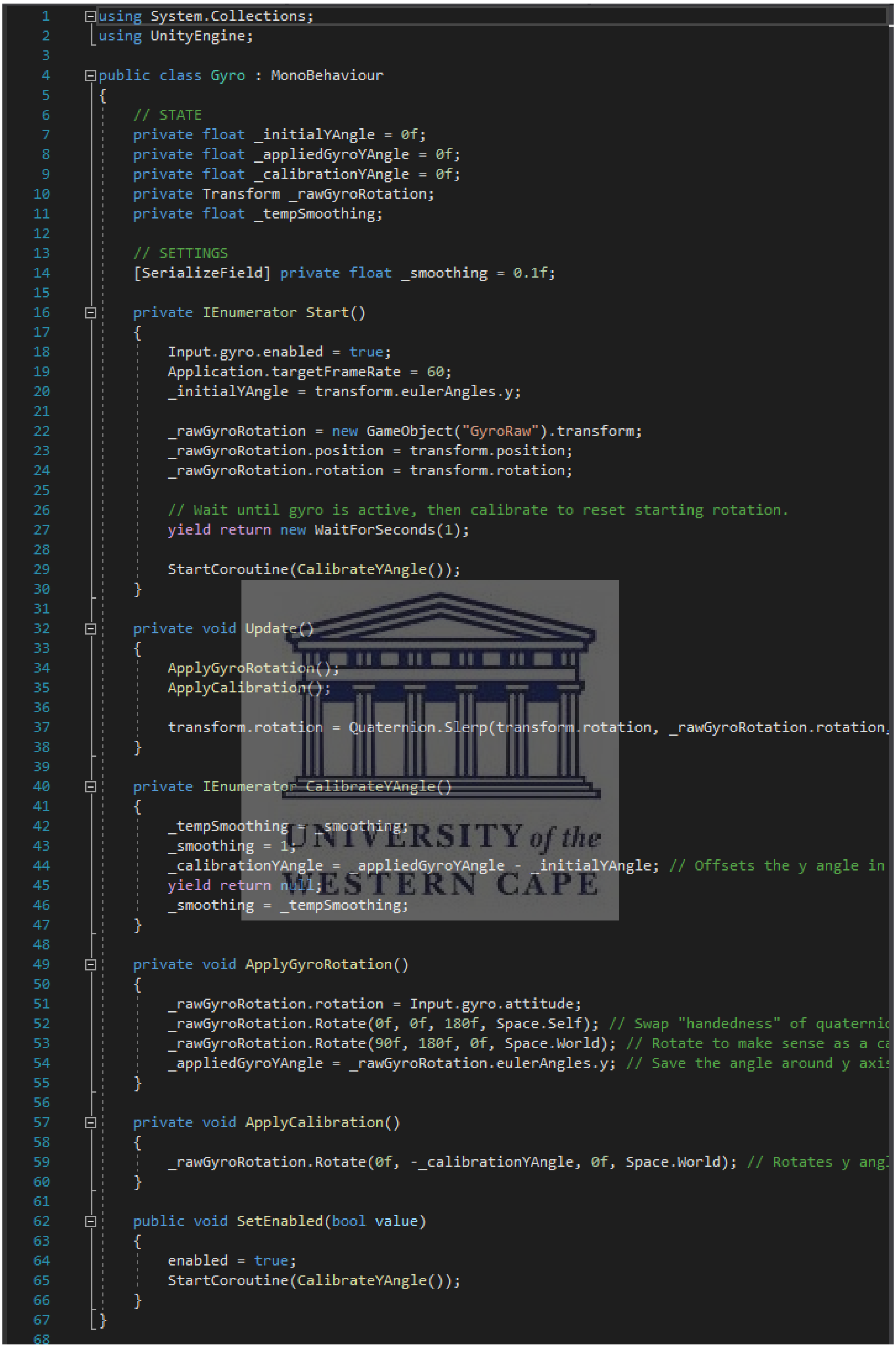
```
using System.Collections;
using UnityEngine;
using UnityEngine.SceneManagement;

public class Scene : MonoBehaviour
{

    public void LoadScene1()
    {
        SceneManager.LoadScene("1.Home");
    }

    public void LoadScene2()
    {
        SceneManager.LoadScene("2.ViewScenes");
    }

    public void LoadScene3()
    {
        SceneManager.LoadScene("3.ARScenes");
    }
}
```

Figure A.2: C# script used to transition between menu UIs.



```csharp
public class DefaultAreaTargetEventHandler : DefaultObserverEventHandler
{
    protected override void OnTrackingFound()
    {
        SetAugmentationRendering(true);
        OnTargetFound?.Invoke();
    }

    protected override void OnTrackingLost()
    {
        SetAugmentationRendering(false);
        OnTargetLost?.Invoke();
    }

    void SetAugmentationRendering(bool value)
    {
        for (var i = 0; i < transform.childCount; i++)
            SetEnabledOnChildComponents(transform.GetChild(i), value);
        SetVuforiaRenderingComponents(value);
    }

    void SetEnabledOnChildComponents(Transform augmentationTransform, bool value)
    {
        var augmentationRenderer = augmentationTransform.GetComponent<VuforiaAugmentationRenderer>();
        if (augmentationRenderer != null)
        {
            augmentationRenderer.SetActive(value);
            return;
        }

        if (mObserverBehaviour)
        {
            var rendererComponent = augmentationTransform.GetComponent<Renderer>();
            if (rendererComponent != null)
                rendererComponent.enabled = value;
            var canvasComponent = augmentationTransform.GetComponent<Canvas>();
            if (canvasComponent != null)
                canvasComponent.enabled = value;
            var colliderComponent = augmentationTransform.GetComponent<Collider>();
            if (colliderComponent != null)
                colliderComponent.enabled = value;
        }

        for (var i = 0; i < augmentationTransform.childCount; i++)
            SetEnabledOnChildComponents(augmentationTransform.GetChild(i), value);
    }

    void SetVuforiaRenderingComponents(bool value)
    {
        var augmentationRendererComponents = mObserverBehaviour.GetComponentsInChildren<VuforiaAugmentationRenderer>(false);
        foreach (var component in augmentationRendererComponents)
            component.SetActive(value);
    }
}
```

Figure A.3: C# code used for AR localization.



```
using System.Collections;
using UnityEngine;

public class Gyro : MonoBehaviour
{
    // STATE
    private float _initialYAngle = 0f;
    private float _appliedGyroYAngle = 0f;
    private float _calibrationYAngle = 0f;
    private Transform _rawGyroRotation;
    private float _tempSmoothing;

    // SETTINGS
    [SerializeField] private float _smoothing = 0.1f;

    private IEnumerator Start()
    {
        Input.gyro.enabled = true;
        Application.targetFrameRate = 60;
        _initialYAngle = transform.eulerAngles.y;

        _rawGyroRotation = new GameObject("GyroRaw").transform;
        _rawGyroRotation.position = transform.position;
        _rawGyroRotation.rotation = transform.rotation;

        // Wait until gyro is active, then calibrate to reset starting rotation.
        yield return new WaitForSeconds(1);

        StartCoroutine(CalibrateYAngle());
    }

    private void Update()
    {
        ApplyGyroRotation();
        ApplyCalibration();

        transform.rotation = Quaternion.Slerp(transform.rotation, _rawGyroRotation.rotation
    }

    private IEnumerator CalibrateYAngle()
    {
        _tempSmoothing = _smoothing;
        _smoothing = 1;
        _calibrationYAngle = _appliedGyroYAngle - _initialYAngle; // Offsets the y angle in
        yield return null;
        _smoothing = _tempSmoothing;
    }

    private void ApplyGyroRotation()
    {
        _rawGyroRotation.rotation = Input.gyro.attitude;
        _rawGyroRotation.Rotate(0f, 0f, 180f, Space.Self); // Swap "handedness" of quaterni
        _rawGyroRotation.Rotate(90f, 180f, 0f, Space.World); // Rotate to make sense as a c
        _appliedGyroYAngle = _rawGyroRotation.eulerAngles.y; // Save the angle around y axi
    }

    private void ApplyCalibration()
    {
        _rawGyroRotation.Rotate(0f, -_calibrationYAngle, 0f, Space.World); // Rotates y ang
    }

    public void SetEnabled(bool value)
    {
        enabled = true;
        StartCoroutine(CalibrateYAngle());
    }
}
```

Figure A.4: C # code used for the gyroscope rotation.

Appendix B

Questionnaire template used to interview crime scene experts.

Q1: What primary details do you capture about a victim?

Q2: What primary details do you capture about a suspect?

Q3: What primary details do you capture about the overall scene?

Q4: What tools or equipment are used when capturing a crime scene?

Q5: Have immersive technologies (AR/VR) ever been used in data capturing?

Q6: During a crime scene re-visitations what do you use as a guide to remember certain elements?

Q7: How many years in the field have you spent as a crime scene investigator?

Q8: Has evidence ever been declared null and void due to human error?

Q9: Have you ever interacted with immersive technologies for crime scene re-visitations?

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